CE340 – Geotechnical Engineering

Laboratory Manual

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ARMEN
LABORATORY
MANUAL
SERIES

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I am, and ever will be, a white-socks, pocket-protector, nerdy engineer—born under the second law of thermodynamics, steeped in the steam tables, in love with free-body diagrams, transformed by Laplace, and propelled by compressible flow.
Neil Armstrong

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1. Visual Classification

Abstract

In various fields of practice that deal with soils, from soil science to geotechnical engineering, the accurate, detailed, and universal description of the soils encountered at a site is key to understanding how those soils will behave and how they will affect the proposed construction. Typically, this is done by classifying the soils into established types based on characteristics such as gradation and plasticity properties. However, rarely are laboratory tests to establish the soil's gradation and plasticity characteristics performed on every sample of soil that is collected. Instead, classifications are initially developed through visual and tactile assessment of the soil by an experienced technician, and laboratory tests are performed only on select samples to verify the initial classification and provide additional details. Furthermore, field personnel will provide descriptions of the soils encountered that go beyond the type of soil to include their color, moisture level, and more. These field observations are critical to understanding the conditions at the site beyond what can be assessed through quantitative laboratory testing.

Visual classification and soil descriptions are a matter of experience and acquired skills. Knowing how to estimate the gradation and plasticity characteristics as well as knowing what additional features need to be noted takes time and practice; however, this lab exercise will introduce a few basics of this process and offer the opportunity to develop descriptions of a few soils similar to those one might encounter in practice. The method presented in this exercise will provide a framework for describing most any kind of soil and promote the thought processes necessary to effectively describe soil conditions based on sensory observations.

Required Standards

ASTM D2488 Standard Practice for Description and Identification of Soils (Visual-Manual Procedures)

1.1 Introduction

Visual-manual classification and description of soils is a process by which the engineering properties of a soil can be estimated and qualitatively described using only visual and tactile assessments.

First, a skilled technician will gather a soil sample in their hand and examine it visually. Items often described based on visual examination include angularity and shape (for coarse sand, gravel, or larger sizes), color (when moist, typically as compared to standard colors), odor, moisture condition (dry, moist, or wet), structure, and particle size information (range of sizes, maximum estimated size, and fineness as applicable).

Next, a series of manual tests can be performed which may include molding, rolling, squeezing, moistening/drying, or the application of a weak hydrochloric acid solution. Manual tests are particularly useful for fine-grained soils (silts and clays) and may be used to assess the consistency (in-place stiffness), plasticity, dried strength, and dilatancy (how readily the sample releases and absorbs water). The application of the acid solution is beneficial for identifying calcium carbonate, a compound commonly found in limestone and dolomite rocks and a common cementing agent in a wide range of soils (coarse and fine-grained soils).

Finally, all of the relevant information gained from these observations is summarized in a soil description and is used to assign a classification (name and group symbol) to the soil. This final description provides a wealth of information to other engineers and scientists without a single lab test being performed. In fact, these descriptions are helpful in the selection of samples for further testing as well as for grouping of similar materials into layers. This procedure is not a substitute for lab tests, but an experienced technician can accurately and effectively describe and classify soils using these means. With time and practice, you may be surprised to find how well your descriptions will coincide with laboratory test results[1]! Make sure to remember what your soils looked and felt like when you get the results from classification lab tests in the next few weeks.

1.2 Objectives

At the completion of this lab exercise, you will have satisfied the following objectives:

1. Visually assess a series of soil samples
2. Assign a color designation to each of the soil samples based on comparison with standard color palettes
3. Estimate the maximum particle size, size range, and shape (as applicable)

[1] Believe it or not, a friendly soil classifying competition can be a good time, though it doesn't make a great party trick unless you routinely bring dirt to parties.

4. Perform a series of manual manipulations to assess the plasticity and dilatancy characteristics of fine-grained soils
5. Develop a description of each soil that includes the applicable information

1.3 Learning Outcomes

At the completion of this lab exercise, you should be able to:

- understand the typical behavior and characteristics of the major types of soil (gravel, sand, silt, and clay),
- perform the necessary visual and manual assessments to classify and describe soils in the field,
- write clear and detailed soil descriptions using the appropriate engineering terminology, and
- understand how to read a soil description and comprehend the relevant information.

1.4 Procedure

The visual classification procedure is divided into three parts: visual assessment, manual assessment, and classification and description development. Depending on the type of soil that you are working with, some visual or manual assessments and description items will not be applicable, so make sure you are thinking through each of the assessments and what type of information you are looking for. Furthermore, this procedure does not include each of the assessments that are included in ASTM D2488 (for instance, you will not perform the HCl reaction or identify organic materials). This is because it has been previously determined that some assessments are not applicable to the soils being considered. In practice, you should review the ASTM standard prior to classifying soils and incorporate as many of the visual and manual assessments as are needed to effectively describe your soil. Remember, the ASTM standard is a prescriptive specification that licensed engineers and engineering firms must follow.

1.4.1 Visual Assessment

To begin, consider the pan of soil before you that you wish to describe. Visually assess the particles for size first. In particular, start by estimating if the majority of the particles are "coarse" or "fine". The standard dividing line between coarse-grained soils (which include sand and gravel) and fine-grained soils (which include silt and clay) is a particle diameter of 0.075 mm. To discern this visually, ask yourself if you can see the individual grains with the naked eye or not. As a rule of thumb, the majority of the particles that make up a coarse-grained soil will be visible to you as individual grains. A couple of example samples are provided in Figure 1 and 2 to show the difference between a sand (coarse-grained soil) sample and a silty clay (fine-grained) soil sample. Estimate if your sample consists of a majority (more than 50%) coarse or fine particles and thereby designate the soil as "coarse-grained" or "fine-grained" soil.

Table 1. Standard particle size categories

	Particle Size	
Name	mm	in.
Boulders	>300	>12
Cobbles	75 to 300	3 to 12
Coarse Gravel	19 to 75	0.75 to 3
Fine Gravel	4.75 to 19	0.19 to 0.75
Coarse Sand	2 to 4.75	0.079 to 0.19
Medium Sand	0.425 to 2	0.017 to 0.079
Fine Sand	0.075 to 0.425	0.0030 to 0.017
Silt and Clay (Fines)	<0.075	<0.0030

Fig. 1. Example of a predominantly fine-grained (silty lean clay) soil sample. Note how the majority of the particles are too small to see individually. The quarter also offers a quick scale comparison.

Fig. 2. Example of fine silty sand sample. Note how here we can see many of the individual particles, but they are still quite small. This is a good indication that they are fine sand particles.

Now assess the particle sizes in a bit more detail. Estimate the maximum particle size that you see, then consider about what percentage of the particles can be sorted into the specified size ranges. Particles will fall into the categories described in Table 1 and ASTM D2488 §3.1[2]. The size categories that are presented in the standard are defined by measured particle sizes (in inches or millimeters). These measurements are typically performed using sieve analysis or hydrometer testing, but for our visual classification, we will have to estimate the particle sizes.

[2] The goofy looking § symbol means "section". Refer to this section of the ASTM standard for detailed information straight from the source.

Estimate the percentage of the particles by volume that fall into the categories of gravel, sand, or fines to the nearest 5% and write down these values. Identify the material that makes up the largest percentage of your material; this will be referred to as the "primary component." Any other components will be included in the description as either a modifier (silty, sandy, gravelly, or clayey), as a "with" component (e.g. sand with silt), or as a "trace" component (sand with trace of clay). Whether the material type is a modifier, "with," or "trace" depends on both the percentage of the other component as well as whether the overall soil is a coarse-grained soil or fine-grained soil (refer to the first paragraph of this section). If your overall soil is a majority coarse-grained soil with some fine-grained soil component, refer to Table 2. If your overall soil is a majority fine-grained soil with some coarse-grained component, refer to Table 3.

Note that Table 3 indicates that if you have a fine-grained soil that contains 30% or more of sand, gravel, or a combination, a modifier should be used (i.e. "sandy" or "gravelly"). In the case of a combination of sand and gravel, utilize the modifier associated with the material that is more prevalent and designate the other as "with" (e.g. if there is more sand than gravel in a majority clay sample, designate the soil as sandy clay with gravel). To determine if fine-grained soils are clay, silt, or a combination we will need to perform additional tests.

Table 2. Wording for fine-grained secondary components of majority coarse-grained soils

Description Term	Percentage Fine-Grained Soil
Modifier	15 or More
"With"	Between 5 and 15
"Trace"	Up to 5

Table 3. Wording for coarse-grained secondary components of majority fine-grained soils

Description Term	Percentage Coarse-Grained Soil
Modifier	30 or More
"With"	Between 15 and 30
"Trace"	Up to 15

The process described above can be a bit confusing. For a visual guide, refer to the flow charts provided in ASTM D2488 Figure 1 for majority fine-grained soils and Figure 2 for majority coarse grained soil. In addition, below are a couple of illustrative examples:

Example

Consider a soil that is 65% sand, 25% gravel, and 10% silt. Because of the combined 90% sand and gravel, this is a coarse-grained soil, so we will use Table 2. Based on the percentage of silt, we would describe this soil as "sand with gravel and silt".

Example

Consider a soil that is 65% clay, 25% sand, and 10% gravel. Because of the 65% clay, this is a fine-grained soil, so we will use Table 3. Based on the percentages of sand and gravel, we would describe this soil as "clay with sand and trace of gravel".

If you refer to the flow charts you will see that fine-grained soils are designated as CL, ML, CH, or MH. "C" is the symbol for Clay, and "M" is the symbol for Silt.[3] CL is a low plasticity or "lean" clay while CH is a high plasticity or "fat" clay. ML is silt while MH refers to an "elastic" silt. These designations are based on plasticity behavior which will need to be determined using the manual tests in the next section of our procedures.

The flow charts also make a distinction between "well-graded" and "poorly-graded" sand or gravel. "Well-graded" sand or gravel contains a wide range of particle sizes and the particles are relatively evenly distributed across this spectrum. "Poorly-graded" sand or gravel will have particles that are all of similar sizes. For visual classification, this is more of an experience based estimate (do the particles range from fine to coarse or are they mostly all fine, medium, or coarse for instance). When we perform our sieve analysis, we will determine the grading using numerical benchmarks.

The next part of our visual assessment is the visible moisture content of the sample. If the material is dusty and dry to the touch, we will describe it as "dry." If the sample is damp but there is no free water visible, we will describe it as "moist." If the sample contains visible free water (that is, water that has not adhering to the particle surfaces), we will describe it as "wet."

The final visual assessment that we will need to perform is describing the color. Compare your soil to the standard color swatches and select the color description that matches best. If your soil has a mix of multiple distinct colors, list the names of each color in order from most prevalent to least (e.g. "brown and yellow" for a soil that is mostly brown with some yellow).

[3] If you're wondering why silt is not "S," it's because that letter was already taken with "sand," so Casagrande selected "M" because *Moh* is the old German word for silt.

1.4.2 Manual Assessments

Identification of fine-grained soils (those with more than 50% "fines" or particles less than 0.075 mm) or fine-grained portions of coarse-grained soils requires a series of manual manipulations designed to assess the plasticity and moisture response behavior of the soils. These tests are outlined in this section.

First we will assess the dry strength of the sample. For this we can use either naturally occurring dry clumps of soil or we can form roughly 1 inch diameter balls and allow these to dry. Make sure that when you select a naturally occurring clump that you do not accidentally select a large piece of gravel! Take each clump or ball into your hand attempt to crumble them. Note how easily or difficultly they break apart. Table 9 in §14 of ASTM D2488 provides a guide for how the dry strength should be described.

Next we will assess the plasticity of our fine-grained materials. To do this, collect a portion of the soil and roll it into a thread in your hand. Think of trying to make a long skinny snake with Playdoh. Attempt to roll the thread until it is about $\frac{1}{8}$ inch in diameter. If the soil easily rolls to a diameter of $\frac{1}{8}$ inch or less without crumbling, ball up the material and roll it again, repeating the process until the material starts to break apart as the thread reaches a diameter of $\frac{1}{8}$ inch. Take note of how easily this process goes and how the thread behaves once formed. Compare your observations to the criteria in Table 12 in §14 of ASTM D2488 and thereby designate the material as non-plastic, or low, medium, or high plasticity.

Now you should have sufficient information to classify your fine-grained soil. Silt (ML) will have low to no dry strength meaning that it will easily crumble when dried. Silt will also be difficult to roll into a thread, crumbling readily when attempted. Elastic silt (MH) will have somewhat higher dry strength and may have low to medium plasticity. Low plasticity or "lean" clay (CL) will have a moderate plasticity and dry strength (higher than either type of silt), while high plasticity or "fat" clay (CH) will have quite high dry strength and plasticity.

If the soil sample is a fine-grained soil (i.e. more than 50% of the material has a diameter smaller than 0.075 mm), the full name and symbol for the fine-grained portion will be used in the description (e.g. sandy elastic silt with gravel, ML). If the soil sample is coarse-grained (i.e. more than 50% of the material is larger than 0.075 mm), only silt or clay will be used irrespective of the plasticity behavior (e.g. clayey gravel, GC).

1.4.3 Classification and Description Development

After performing our assessments, we now want to develop a full description of our material. Figure 3 presents a couple of example descriptions with the parts numbered. The items we need to include in our description are as follows.

1. Moisture Content
2. Color
3. Soil Classification (Name and Symbol)
4. Fineness (fine, medium, coarse for sand or fine, coarse for gravel)

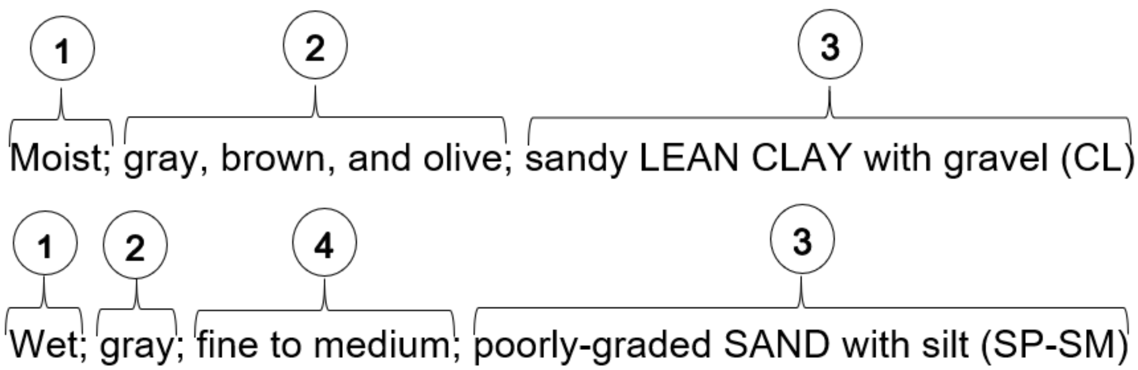

Fig. 3. Example soil descriptions

1.5 Summary

Now we have completed the process of visually and manually evaluating our soil samples and developing a thorough description based on the results. With these descriptions, other engineers will have a good idea of how our soils look and behave including color, gradation, plasticity, and as-sampled moisture level. We have also learned the basics of how to evaluate soils through visual and tactile means, and how to coherently describe the soils to others. We are now poised to expand this knowledge to describe more complex conditions and to assess soils on a full range of properties as described in the ASTM standards.

2. Sieve Analysis Procedure

Abstract

A soil's gradation characteristics are one of the fundamental properties that can describe a material in sufficient detail to classify and utilize the material in a wide variety of applications. Numerous agencies and code bodies (i.e. state highway agencies (SHAs), International Building Code (IBC), American Concrete Institute (ACI), Superpave, etc.) all use gradations to ensure materials such as backfill, structural fill, and pavement mixtures have adequate strength and durability. The gradation itself is a description of the amount of material present at a set or range of specific sizes. For example, part of a gradation analysis may determine that a soil sample has particles that are 65%, by weight, smaller than 0.5 inches.

Required Standards

ASTM C136 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates

ASTM D6913 Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis

ASTM E11 Specification for Woven Wire Test Sieve Cloth and Test Sieves

The following specifications are optional, but they are listed here in the event more information is needed to complete the laboratory exercise:

ASTM D6026 Standard Practice for Using Significant Digits in Geotechnical Data

2.1 Introduction

A sieve[4] analysis is a process in which the soil material is separated into various sizes by using a combination of sieves. A sieve is typically a round or rectangular frame that has a wire cloth inside it. This cloth is a precisely woven material that has a specific opening size as outlined in ASTM E11. Multiple sieves are stacked in descending size to perform the analysis. This sieve stack is then physically or mechanically agitated to ensure all the particles have a chance to fall through the openings in the wire cloth. Finally, the amount retained on each sieve is weighed and the results can be plotted.

2.2 Objectives

At the completion of this lab exercise, you will have satisfied the following objectives:

1. Perform sieve analysis on a silty-clayey soil material
2. Perform sieve analysis on a sandy soil material
3. Perform sieve analysis on a coarse aggregate
4. Perform calculations necessary to determine the requisite gradation properties
5. Construct gradation chart of three aforementioned materials down to a #200 (75 μm) sieve size

2.3 Learning Outcomes

At the completion of this lab exercise, you should be able to:

- understand what a sieve is and how a sieve stack is utilized to obtain gradation information
- perform calculations necessary to characterize the gradation of a sieve analysis
- understand how to interpret a gradation chart and fineness modulus values when provided with specification requirements
- present information on gradations in a useful and professional manner

[4] Pronounced “sive” like “give”; not “seeve” like “grieve”. Surest way to look like a rookie in front of your new boss!

2.4 Procedure

The sieve analysis procedure is divided into three parts: preparation, execution, and analysis. Given the importance placed on accurate sieve analyses, it is critical to keep accurate notes and follow steps carefully and accurately. When an engineer presents their stamped work to a client, a phrase similar to "the values were determined in accordance with ASTM D6913" will be included. This is not a generic phrase! You are legally stating you followed **all** of the requirements outlined in the specification. If you skipped a step, and the client found out or suspected the numbers were off, they would have legal standing to challenge your results. If you did follow the specification exactly, then you can correctly use that phrase. If you did not, one alternative is "the values were determined using generally accepted procedures such as ASTM D6913 and others". However, if you were a client, would you want a firm to follow specifications exactly or one that gets most of it?

We are going to run two sieve analysis procedures: ASTM C136 and ASTM D6913. They are fairly similar with a few specific differences. The ASTM C136 procedure is typically used on aggregate sources for concrete and asphalt mixtures. It is a simpler procedure because it assumes there are no significant amount of fines[5] present in the sample that are plastic[6]. The ASTM D6913 is better suited for soils with significant amount of fines as the test method specifies procedures to separate the fine particles.

Regardless of which procedure to use, the size of the sieves are governed by ASTM E11. There are three general ways to identify a sieve: number, opening in millimeters, and opening in inches. Each sieve has a nameplate attached to it that identifies its size and that it meets ASTM E11 (Fig. 4).

Fig. 4. Example of sieve nameplate. This is a #10 sieve which has an opening of 2 mm or 0.0787 inches. Note that the ASTM E11 designation is also indicated.

[5]Recall that fines are usually considered particles smaller than the #200 sieve (75 μm).
[6]The topic of plasticity is covered in the companion Atterberg Limits laboratory exercise.

2.4.1 Preparation

In performing this lab procedure, we can characterize soil and aggregate materials with varying grain sizes including fine-grained soil (silt or clay), coarse-grained soil (sand or gravel), and coarse aggregate. Fine-grained soils will be characterized with ASTM D6913 and the coarse-grained soil or coarse aggregate will be characterized with ASTM C136. The actual sieve sizes we use are minimally specified; that is, the specification outlines the minimum sizes we should use but we could add additional sizes depending on our objective. For this exercise, we will stick with the minimum requirements.

The minimum requirements for ASTM C136 are in §8.2[7] and simply state that the minimum sieves are those specified by the client or agency. For characterization of our sandy soil sample, the required sieves are: #4, #8, #16, #30, #50, #100, and #200 (Fig. 8). These particular sieves are chosen so that the fineness modulus can be calculated for the sandy soil sample as described in ASTM C136 §9.2. As we do not typically calculate a fineness modulus for coarse aggregate, we will use the following sieves when characterizing coarse aggregate: 37.5 mm, 25 mm, 12.5 mm, 9.5 mm, and #4. For all the sieves stacks, do not forget the pan and lid (Fig. 5)

Fig. 5. Examples of the lid (left) and pan (right) that are required for each sieve stack.

The minimum requirements for ASTM D6913 are in §6.1.1 and Table 1 within the standard and apply to the silty-clayey soil. Because this method is designed for soil materials that can have a wide range of particle sizes, there are significantly more sieves. So many, in fact, that we split the test into two "runs".

[7]The goofy looking § symbol means "section"; so this is telling you to look at section 8.2 in the specification.

The sieve analysis procedure is done on a weight-basis (i.e. all calculations are done using weights, not volumes). We are going to be recording a variety of weights[8] and it is important to prepare a worksheet prior to lab to aid in collecting the necessary data.

To aid us in creating a worksheet, let's think about what we want at the end of the test: weight of aggregate sitting on each sieve. Well, we could shake the sieve stack, separate the sieves, then dump the amount in each sieve on the scale and measure it. However, with the smaller sieve sizes, it is really difficult to get all the particles out of the woven cloth. Thus, our measurements are likely to be off, and in some cases significantly off! So, we need to first measure the weight of the empty sieves, run the sieve analysis, then weigh the sieve with the retained material. We can then subtract the weight of the empty sieve and obtain the retained mass! An example data collection worksheet is shown in Appendix A.

As you weigh each sieve to obtain the empty weight, be sure to inspect it for leftover aggregate (Fig. 6) or damaged/torn mesh (Fig. 7). Once you have all the sieves weighed, arrange the stack of sieves so that the largest opening sieve is at the top of the stack and the opening decreases as you go down the stack (Fig. 8).

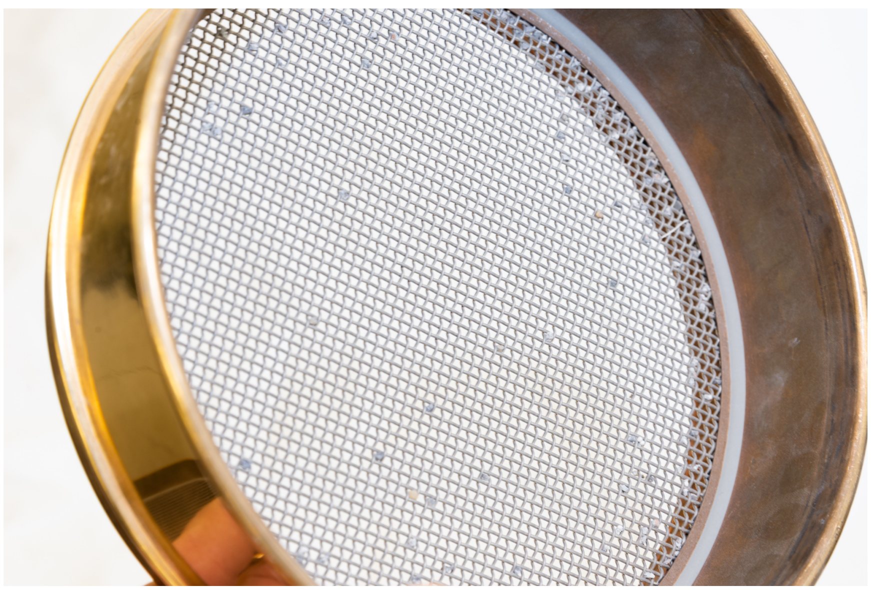

Fig. 6. An example of a #10 sieve with aggregate particles still stuck in the mesh. These should be carefully removed to ensure accurate results.

[8]For this laboratory exercise, weight and mass are used interchangeably. Since the materials being measured are not moving and we assume the gravitational force exerted on them is constant, we can safely make this assumption. Additionally, we are not calculating the force exerted by the materials. In other parts of this course, we will distinguish between weight and mass using gravity.

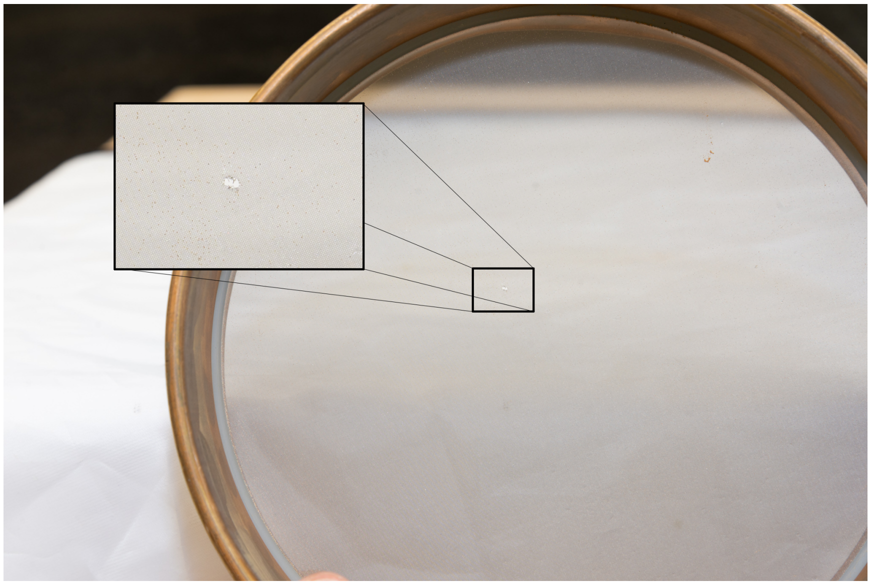

Fig. 7. An example of a torn mesh in a #200 sieve. Even a hole as small as this can cause significant errors to develop in your analysis.

Fig. 8. An example of a properly stacked sieve set. This example is purposely made up of sieves from various companies and ages to demonstrate the variety in the nameplates. Even the ugly ole #30 sieve needs some lovin.

We will also need the starting weight of the material. It is possible to sieve too much material and get erroneous results. Fortunately, both specifications outline the maximum allowable on the individual sieves and total starting weights. For ASTM C136, this starting sample weight information is found in §7.3 and §7.4 for fine aggregate and coarse aggregate, respectively. The overload weight for each sieve for ASTM C136 is found in §8.3. For ASTM D6913, this starting sample weight information is found in §10.2. The overload weight for each sieve for ASTM D6913 is found in §11.3.

Checklist

- ☐ Obtain correct sieves, note any missing sieves
- ☐ Weigh empty sieves, including the pan
- ☐ Determine minimum weight of material needed for test
- ☐ Record starting sample weights

2.4.2 Execution

We are now ready to run the sieve analysis. For both specifications, the end goal is to separate the particles into their individual sizes. Both specifications describe manual and mechanical agitation methods to expedite the sieving process. For this laboratory exercise, we will utilize mechanical shaking methods for both procedures.

Neither specification outlines a precise time to shake the sieves. This is because soil materials do not sieve equally. Both specifications outline trial procedures to use to determine the amount of time to sieve a sample. A typical shaking time for ASTM C136 materials is 5–10 minutes whereas ASTM D6913 materials have shaking times around 15–20 minutes. For this laboratory exercise, the ASTM C136 test will be run with a shaking time of 5 minutes and the ASTM D6913 test will be run with a shaking time of 10 minutes.

Because the sieves are expensive and damage can occur if they are not loaded into the sieve shaker properly, the instructor will assist you with this process. Make note if the correct shaking time is used. An example of a properly loaded sieve stack is shown in Figs. 9, 10, and 11.

Fig. 9. An example of a sieve stack loaded into a mechanical shaking device and the timer set for 7 minutes.

Fig. 10. An example of a sieve stack loaded into a mechanical shaking device and the protective tamping plate placed on top of the sieve stack. The cork or rubber in the center of the plate should be intact. If missing, notify the instructor as damage may occur if not present.

Fig. 11. An example of a sieve stack loaded into a mechanical shaking device and the protective tamping plate placed on top of the sieve stack with the tamping arm from the shaker resting on the tamping plate. At this point, the sieve stack is ready to be mechanically shaken, not stirred.

After the shaking period has ended, the sieve stack will be removed from the shaker. The next step is one of the hardest steps for this entire process: separating the sieve stacks without spilling material. The sieves have been pounded together and particles have wedge themselves in-between the sieves. The instructor will demonstrate the technique to use to correctly separate the sieves.

With the sieves now separated, they can be individually weighed. If material was lost during the separation process, note it in your report but perform the calculations with the values you measure. Do not attempt to guess how much material was lost. You may notice that some sieves appear empty. You should still weigh them. If there was a particle stuck in the mesh prior to the shaking process and it came loose, you will see a decrease in the apparent mass, indicating you were not careful in the preparation of the test.

Checklist

☐ Select correct shaking time for material being sieved

☐ Carefully separate sieve stack after shaking period

☐ Record weights of individual sieves with retained aggregate

☐ Dump retained aggregate and clean each sieve

2.4.3 Analysis

We should now have enough data to calculate and plot the gradation of the three materials characterized in the laboratory exercise. The first thing to do is calculate the mass of material on each sieve. You have likely figured out by now we simply subtract the empty weight of the sieve from the weight of the sieve with the material in it. At this point, the individual masses should be summed to see how close it is to the original starting mass. This is a very important check as any discrepancy would indicate that material was lost during the test. The maximum allowable loss of material is 0.3% for ASTM C136 procedures. Interestingly, ASTM D6913 does not specify a maximum allowable loss.

With individual retained weights and the summed weight, we can calculate the percentage retained on each sieve. With the retained percentages on each sieve, we can then calculate a cumulative, or running total, of percentage retained. Finally, the cumulative passing is simply 100% minus the cumulative retained. An example dataset is shown in Table 4 and can be used to check the spreadsheet you develop for this laboratory exercise. Note that the #200 sieve value for cumulative retained goes to one decimal place. This is required by ASTM C136 §10.2. There are a couple of checks one can do to ensure the calculations are correct:

- Cumulative retained must always end at 100% at the pan.
- Cumulative retained values must always increase from sieve to sieve down the stack.
- Cumulative passing must always end at 0% at the pan.
- Cumulative passing values must always decrease from sieve to sieve down the stack.

Example

Table 4. Example calculations of gradation data which can be used to check your spreadsheet.

Sieve	Sieve [g]	Sieve + Agg [g]	Agg [g]	Retained [%]	Cuml. Retained [%]
No. 4	721.51	744.87	23.36	3	3
No. 8	436.15	487.45	51.30	6	9
No. 16	393.18	449.90	56.72	6	15
No. 30	350.82	455.55	104.73	11	26
No. 50	558.74	959.93	401.19	44	70
No. 100	317.71	565.17	247.46	27	97
No. 200	248.41	269.95	21.54	2.4	99.4
Pan	355.94	365.46	9.52	1.0	100.0

The spreadsheet you develop for this laboratory exercise should be able to automatically calculate the gradation with the only inputs being the empty sieve weight and sieve weight with retained material. All other calculations should be automatic and done with equations in the spreadsheet. Please use the example data above to check your spreadsheet[a].

[a] You may be excited to point out that I am not using consistent decimal places for the Retained and Cuml. Retained columns, but ASTM allows me to report the #200 sieve and smaller to one decimal place provided the value is less than 10%.

This fineness modulus is typically used for daily quality control at a quarry or ready-mix plant to monitor the aggregate sources for changes. In some cases, agencies will specify a minimum and maximum fineness modulus value for a project. A lot of times, the fineness modulus is abbreviated FM and is typically only used on fine aggregates, but can be used on coarse aggregates. As previously mentioned, the specifics of the calculation are in ASTM C136 §9.2.

Example

Given the example data below, the calculated FM would be 2.76 (Table 5). The hardest part about calculating the fineness modulus is remembering which sieves to use (look them up!) and the fact that the calculation uses the cumulative retained, not cumulative passing or percent finer.

Table 5. Example dataset for FM calculation.

Sieve Size	Ret., %	Cuml. Ret., %
3/8"	0	0
#4	2	2
#8	13	15
#16	25	40
#30	15	55
#50	22	77
#100	10	87
#200	10	97
Pan	3	100

Checklist

☐ Calculate cumulative retained and cumulative passing for all three soil material sources

☐ Calculate the FM of the sandy soil sample

2.5 Summary

We have successfully planned, executed, and analyzed the results of a sieve analysis on three different materials using two different ASTM specifications. This relatively straightforward process forms the basis of numerous engineering endeavors. All disciplines within civil engineering utilize gradation information for hazardous waste diffusion, concrete mixture design, slope stability, etc.

However, the test methods used to obtain the gradation data are sometimes insufficient. You may have noticed that the silty-clayey soil sample had a significant amount of material that passed the #200 sieve. We need a method to evaluate the gradation to an even smaller particle size. Why? We need to know how much clay and silt we have in our sample as these materials can significantly affect the behavior we encounter in the field.

3. Hydrometer Testing Procedure

Abstract

The hydrometer test indirectly characterizes the gradation of materials that are extremely small (i.e. particle size is less than 75 μm). In this method, the sample is blended in a high-shear mixer and then allowed to settle out over time. The change in density is measured over time and from Stokes Law, the particle sizes can be calculated.

Required Standards

ASTM D7928 Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis
ASTM E11 Specification for Woven Wire Test Sieve Cloth and Test Sieves

The following specifications are optional, but they are listed here in the event more information is needed to complete the laboratory exercise:
ASTM D6026 Standard Practice for Using Significant Digits in Geotechnical Data
ASTM E100 Specification for ASTM Hydrometers

3.1 Introduction

The hydrometer testing procedure is an interesting procedure that indirectly measures the particle sizes of a soil sample that are smaller than the #200 sieve (75 μm). The keyword here is indirect measure. While it is possible to purchase sieves that have incredibly small openings, they are, as expected, incredibly expensive! Not to mention extremely fragile and easily clogged.

A hydrometer solves this issue as it is simple, requires no batteries, and maintains calibration relatively well (Fig. 12). When we place the hydrometer into a milkshake of soil sample, it will float to a certain level, due to the density of the solution. As the "milkshake" settles out, the density changes and the hydrometer slowly floats to a different level.

Fig. 12. An example of an ASTM 152H hydrometer.

This is where Stokes' Law comes into play. We first make several assumptions to use Stokes' Law: smooth, perfectly round particles and the particles do not interact with one another. For certain soils, this assumption can be quite a bad one to make. But we do not have a much better option when it comes to the cost and ease of running the hydrometer test.

With those assumptions, Stokes' Law is given by Eq. (1):

$$F_d = 6\pi\mu R v \tag{1}$$

where:

$F_d =$ friction force between particle and fluid

$\mu =$ dynamic viscosity

$R =$ radius of particle

$v =$ velocity of fluid or particle

However, Eq. (1) is not useful for a hydrometer analysis. We are only measuring density changes! If we do some rearranging and most importantly, assume the particles are falling at their terminal velocity within the fluid, we get a more useful form of Stokes' Law given by Eq. (2):

$$v = \frac{2\left(\rho_p - \rho_f\right) g R^2}{9\mu} \tag{2}$$

where:

$\rho_p =$ mass density of particle

$\rho_f =$ mass density of fluid

$g =$ acceleration due to gravity

Almost there! We rearrange Eq. (2) to its final form which is in terms of diameter of particle[9]. The final form of the equation used in ASTM D7928 is Eq. (3):

$$D = \sqrt{\frac{18\mu v}{g\rho_f\left(\rho_p - 1\right)}} \tag{3}$$

where:

$D =$ diameter of particle

The actual equation in ASTM D7928, as you will see when you perform the calculations, is slightly different than Eq. (3) in that the particle velocity, v, is calculated as the time it takes a particle to fall from an effective depth.

[9] We want diameter over radius because our normal sieve analysis is giving us the particle diameter.

3.2 Objectives

At the completion of this lab exercise, you will have satisfied the following objectives:

1. Perform a hydrometer test on a silty-clayey soil material
2. Perform a hydrometer test on a sandy soil material
3. Perform the calculations necessary to determine the gradation values smaller than the #200 (75 μm) sieve
4. Construct a gradation chart of the two aforementioned materials over the complete range of particle sizes (i.e. combine the sieve analysis and hydrometer analysis)

3.3 Learning Outcomes

At the completion of this lab exercise, you should be able to:

- understand how Stokes' Law is applied to soil gradation measurements
- perform calculations associated with hydrometer measurements to determine gradation values
- understand how to combine sieve analysis and hydrometer testing values to form a complete gradation of a soil material
- present information on gradations in a useful and professional manner

3.4 Procedure

The hydrometer testing procedure is divided into three parts: preparation, execution, and analysis. The testing procedure is relatively straightforward, however, unlike the sieve analysis procedure, it is easier to make measurement errors. If you brew your own beer or are picky with your engine coolant blend ratio, you may already be familiar with how to use a hydrometer and how difficult it can be to actually observe the reading on it.

This test is also extremely sensitive to temperature changes. Recall from Eq. (3) that there is a viscosity term, μ. This is an important consideration and the test method attempts to minimize the effects of temperature.

3.4.1 Preparation

We have two materials to be analyzed: a silty-clayey soil and a sandy soil. If we read ASTM D7928 §1.2, it states that clean sands cannot be effectively characterized with this method. We will see if our sandy soil has enough fines to be characterized with the hydrometer test method. The minimum sample weight we need is specified in ASTM D7928 §3.2.4 with the #10 (2 mm) sieve used as the separation sieve. It is important for you to note the hydrometer type (either 151H or 152H) as each one measures values in different units.

The sample itself is usually in some sort of moist condition. The hydrometers we will use can only "handle" a certain amount of soil in solution. It is also important to keep the sample sufficiently sealed as you prepare to execute the procedure[10]. So, if we are weighing a moist sample, the weight we record will be some amount of solids (i.e. the soil) and some amount of water. The 151H hydrometer can handle 45 g of solids and the 152H hydrometer can handle 55 g of solids. The ASTM D7928 specification provides an equation to estimate the amount of moist soil we can add to get close to the capacities of the hydrometers and is shown[11] in Eq. (4):

$$M = H_c \times \left(\frac{100}{P_{200}}\right) \times \left(1 + \left(\frac{w_c}{100}\right)\right) \tag{4}$$

where:

$M =$ mass of sample to weigh

$H_c =$ capacity of hydrometer (i.e. 45 g or 55 g)

$P_{200} =$ percent passing the #200 sieve, as a percent (i.e. 3.4%)

$w_c =$ estimated moisture content, as a percent (i.e. 5.2%)

[10]See Note 9 in §9.1 for why.

[11]The variable names have been simplified compared to those listed in ASTM D7928 §9.5.

Weigh out an amount of moist soil that is close to the value calculated using Eq. (4). Then weigh out another amount of soil that is of similar weight. This second specimen will be oven-dried to determine the actual moisture content so that your later calculations can be performed.

The ASTM D7928 specification outlines procedures to check the calibration of the hydrometer. We will skip those procedures but be aware that these checks should be performed on a routine basis. Generally the hydrometer is sufficiently calibrated if it does not have any cracks or chips. Part of this calibration process determines the "effective depth" of the hydrometer. You will be provided this "effective depth" value.

Sometimes the soil material will flocculate, or clump together, when it is mixed in water. This can significantly affect the measurements and does not represent the true particle size distribution. The ASTM D7928 specification allows for the addition of a deflocculant: sodium hexametaphosphate. The use of this dispersant is based on general knowledge of the soil type being analyzed. Its use is not always required. For this laboratory, it is only used for the clayey-silty soil. The dispersant is added to the moist soil sample. Weigh out approximately 5 g of the sodium hexametaphosphate and record the exact amount that was added.

The final part of the preparation is to determine the meniscus correction factor for the hydrometer. Because the test procedure allows for varying amounts, or no amount, of a deflocculant, there is not a single meniscus correction factor that can always be used. It should be characterized each time the test is run and is relatively easy to determine. Recall from your basic chemistry courses that the meniscus is the curved part of water at the interface of a vertical surface. Most of the time, we read from the bottom of the meniscus however, during this test the water starts cloudy and it is usually impossible to read from the bottom of the meniscus. So we will read from the top of the meniscus and correct the measurement using a correction factor, C_m. You will use the difference in height, in units of hydrometer markings, to correct your readings as shown in Fig. 13. Do your best to read to the nearest 1/4th division of the printed markings (Fig. 14).

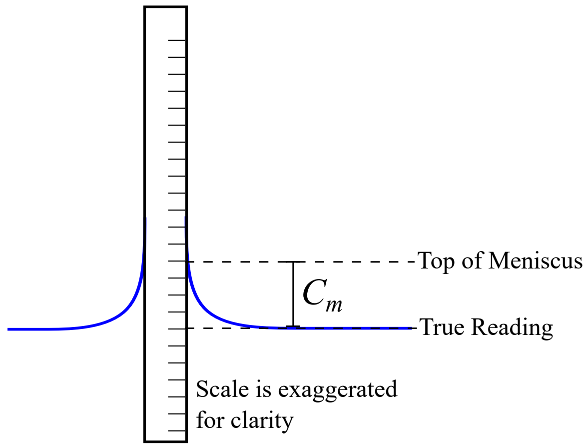

Fig. 13. Schematic of true and top of meniscus reading locations. The resulting correction factor, C_m, is shown as the difference between the two readings.

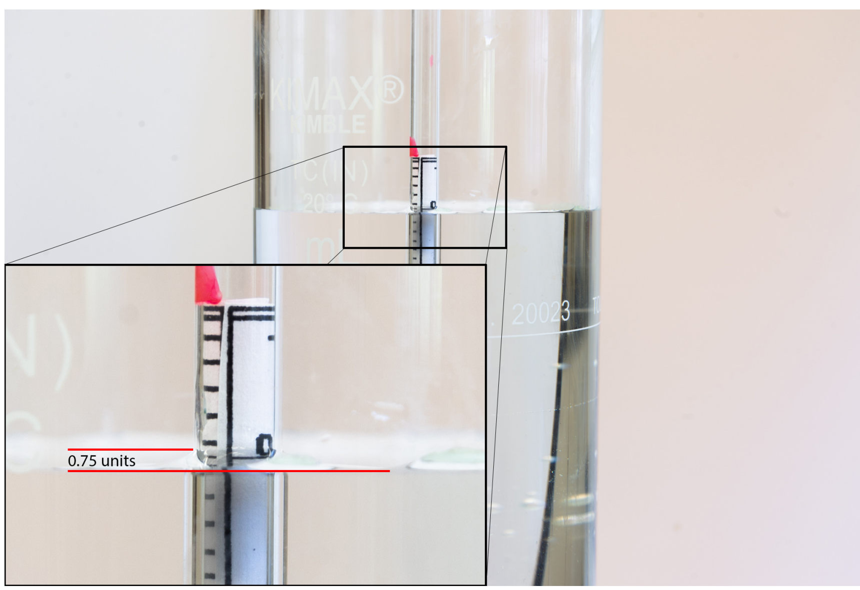

Fig. 14. Example of an actual meniscus correction factor reading using a 152H hydrometer. Note that you must approximate to the nearest 1/4th division on the scale.

Checklist

☐ Record the weight of the moist soil sample

☐ Record the weight of a second sample to oven dry for moisture content

☐ Record the weight of the deflocculant

☐ Determine and record the meniscus correction factor

3.4.2 Execution

The ASTM D7928 test procedure is relatively straightforward. The precise details are described in ASTM D7928 §11. For this laboratory exercise, we are using the referee stirring apparatus (i.e. milkshake-style blender) and referee agitator. The procedure involves an overnight rest period for the slurry to completely deflocculate. We will not employ the overnight conditioning period for this laboratory exercise.

The previously weighed sample is blended using a milkshake-style blender to homogenize and deflocculate the slurry. The blender cup should contain all of the weighed sample and enough of the test water, with or without the dispersant, depending on the sample, to fill the cup about halfway. The soil slurry should be blended for about 1 minute.

After blending, transfer the slurry to the sedimentation container. To get 100% of the slurry out of the blender cup, use a squirt bottle containing the test water, with or without the dispersant, depending on the sample, to rinse out the cup completely. Then fill the sedimentation container up to the 1000 mL line with the test water, with or without the dispersant, depending on the sample. You will then use the agitator to homogenize the slurry. You will start with the agitator near the bottom of the sedimentation container, using an smooth up and down motion. Watch the accompanying video to see this process more clearly. Agitate the solution for about 1 minute.

At this point, the slurry would normally be left to condition overnight. However, we will continue with the test procedure as described in ASTM D7928, resuming at §11.7.2. As soon as you remove the agitator from the sedimentation container, start a timer. Your first reading with the hydrometer will occur at the 1 minute mark, so ensure you have everything ready.

Approximately 20 seconds before the 1 minute mark, slowly guide the hydrometer into the soil solution. Be careful and do not allow the hydrometer to spin or bob. Ideally, you lower the hydrometer in the soil solution and when you notice it is neutrally buoyant, carefully release your grip. You want to have the hydrometer stabilized so that precisely at the 1 minute mark, you can take a reading. You will read the hydrometer from the top of the meniscus as described earlier.

Once you have obtained your reading, slowly and carefully remove the hydrometer. It should take you about 15 seconds to remove it from the soil solution. You are trying to minimize the disturbance of the solution and do not want to affect the particles from settling out. Once the hydrometer is removed, measure the temperature of the soil solution using the provided thermometer. The remaining times at which you must take a reading are listed in ASTM D7928 §11.8. Note that the next time is at 2 minutes from the point the agitator left the soil solution and no, you cannot leave the hydrometer in the soil sedimentation container to take that reading.

Each time you remove the hydrometer, you should rinse it off, dry it completely, and return it to the reference sedimentation container. This reference container only has water or water with the dispersant in it. The appendix[12] of ASTM D7928 has two examples of data collection sheets that might be useful references for designing your own to record the experimental data. Namely, X1.1, X1.2, and X1.7 provide good references.

After the last reading, the slurry will be rinsed through a #200 sieve. The material retained on the #200 sieve will be oven dried and then weighed. This data will be provided to you.

Checklist

☐ Record the hydrometer reading at the specified times

☐ Record the soil solution temperature at the specified times

3.4.3 Analysis

The analysis of the hydrometer data is more involved than the sieve analysis. The calculations are described in detail in ASTM D7928 §12. You should go step by step and create a spreadsheet to perform the calculations. To help you setup your spreadsheet, the following flowchart (Fig. 15) describes the calculation process for each reading. After you setup your spreadsheet, it is recommended that you check your calculations with the two examples provided in the appendix (Fig. X1.1 and X1.2).

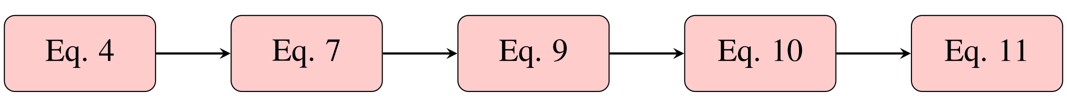

Fig. 15. Flowchart of hydrometer calculations referencing the equation numbers in ASTM D7928. This flowchart uses the equations for the 152H hydrometer used in lab. Other equations are necessary if a 151H hydrometer was used.

The second part is incorporating the hydrometer readings into your previous sieve analysis. If you notice, the hydrometer particle size analysis "starts" at the #200. It combines all

[12]Not the annex, but appendix. They are both at the end.

the particles that are larger than 75 μm together. We cannot directly add the particle size distribution from the hydrometer to the end of the sieve analysis and call it a day. We must put the data in context of the entire gradation.

Example

The easiest way to explain this is to go through an example. A hydrometer dataset is shown in Table 6. Let's also use the gradation shown in Table 5. There is 3% passing the #200 sieve. But wait, we have 56% finer as the first value in our hydrometer analysis! We need to normalize the hydrometer values to the amount that passed the #200 sieve in our sieve analysis. For instance, in the hydrometer analysis, we have 56% passing the 0.0450 mm size. In the context of the whole gradation, that is 56% of 3%, which is 1.68%. That means at the 0.0450 mm size, we have 1.68% passing in the context of the whole gradation. We continue the trend for all the measured particle sizes from the hydrometer analysis.

Table 6. Example dataset from hydrometer testing.

D, mm	Mass % Finer, N_m
0.0450	56
0.0331	32
0.0261	21
0.0174	14
0.0120	11
0.0099	9
0.0071	5
0.0028	4
0.0013	3

Checklist

☐ Calculate particle sizes from hydrometer readings and associated mass percent finer values

☐ Incorporate the hydrometer values into the overall gradation data

3.5 Summary

We have successfully planned, executed, and analyzed the results of a hydrometer analysis on two different materials using ASTM D7928. This test procedures provides critical information about the clay and silt components of a soil and can allow us to make important design decisions. Although there are more accurate methods to determine small particle sizes, the hydrometer test method is straightforward, simple, and cheap.

4. Atterberg Limits

Abstract

Atterberg limits describe a soil's response to changing moisture conditions. There were six limits originally defined by Albert Atterberg in the early 1900s. However, the two that are most important in civil engineering applications are the plastic limit and liquid limit. The plastic limit corresponds to the moisture state in which the soil transitions from a semi-solid state to a plastic state. The liquid limit corresponds to the moisture state in which the soil transitions from a plastic state to a liquid state. These two parameters can then be used to calculate a plasticity index which is used in soil classification. Additionally, the engineering behavior of soils has been well correlated to these limits and index and provides a quick gut check for the expected behavior for a soil.

Required Standards

The following specifications are required to complete this laboratory exercise:

ASTM D2487 Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)

ASTM D4318 Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils

The following specifications are optional, but they are listed here in the event more information is needed to complete the laboratory exercise:

ASTM D6026 Standard Practice for Using Significant Digits in Geotechnical Data

4.1 Plastic Limit Test

The plastic limit test is a relatively simple test that requires almost no equipment. A sample of moist soil is rolled into a string. When the string reaches the required diameter and is just beginning to break apart, the moisture content is measured. This test identifies the transition between a semi-solid state to a plastic state. Think of it like the transition between Play-Doh® that has been left out for a day (i.e. semi-solid) to brand new Play-Doh® (i.e. plastic). Students often misinterpret the term "plastic", thinking it means something hard and rigid. However, we are using the term "plastic" to indicate that if we deform the material, the deformation is permanent, that is "plastic", but it does not fracture or break the specimen to any noticeable degree. This test is typically performed on fine grained soils or the fine grained portion of mixed soils. Soils with insufficient cohesion to be rolled are considered non-plastic and are classified as silts.

4.2 Objectives

At the completion of this lab exercise, you will have satisfied the following objectives:

1. Perform a series of plastic limit tests on a silty-clayey soil material
2. Perform calculations necessary to determine the plastic limit

4.3 Learning Outcomes

At the completion of this lab exercise, you should be able to:

- understand the difference between semi-solid and plastic state of a soil material
- perform calculations necessary to determine the plastic limit of a soil material

4.4 Procedure

The plastic limit test procedure is divided into three parts: preparation, execution, and analysis. ASTM D4318 §16.1 requires that the sample used for the plastic limit test be from the liquid limit test. However, for purposes of this lab, you will use a separately conditioned sample. You will repeatedly evaluate the material until it reaches a consistency at which it can be molded in your hands without sticking. The you will roll it into a string. This will be done at several moisture contents and the one at which it just begins to crumble is the plastic limit.

4.4.1 Preparation

You will need four pieces of equipment for this procedure: glass plate, a comparison rod that has a 3.2 mm diameter, two sample containers (Fig. 16), and a scale. This glass plate provides a smooth surface upon which to roll out your soil sample. The comparison rod will assist you in determining if your rolled sample is of the correct diameter.

Fig. 16. Aluminum sample containers that can be used for Atterberg limit tests. There is no requirement on the required size of the sample can, just that it can sufficiently hold the material to be oven dried.

You will also need about 20 g of prepared soil. You should note that the provided soil material completely passes the #40 sieve (425 μm). Your hands at this time should be clean and dry. Finally, measure the empty weights of the two sample containers and label them with sufficient detail that you can identify them at a later time.

Checklist

☐ Obtain glass plate, comparison rod, and two sample containers

☐ Obtain about 20 g of prepared soil

☐ Obtain the empty weight of the two sample containers and label them

4.4.2 Execution

The execution process is straightforward. You will continually roll a sample of prepared soil into a 3.2 mm diameter thread. Each time you approach the specified diameter, you will observe the sample to see if it is breaking apart. If your childhood was filled with Play-Doh®, this should be a relatively easy task.

First you will obtain 1.5–2.0 g of prepared soil sample and form it into an ellipsoidal shape. Then, on the glass plate, roll the sample with your fingers or palm to achieve a uniform thread with a diameter of 3.2 mm. You must achieve this diameter within two minutes of starting to roll. You can roll back and forth relatively quick and a rate of 80 to 90 back and forth motions per minute is recommended.

Once a thread with a diameter of 3.2 mm is obtained, break the thread into several pieces. Knead the pieces together to reform a new ellipsoid shape. Re-roll this new ellipsoid in the same manner as before to achieve a 3.2 mm thread. Continue this process of rolling, reforming, and re-rolling until the thread crumbles and is unable to be formed into a 3.2 mm diameter thread.

Once you have a sample that crumbles at or before it reaches 3.2 mm in diameter, collect the sample and place into a sample container and seal. Continue the test with a new 1.5–2.0 g sample. When that sample crumbles, place into the same container as before. Repeat the procedure until you have at least 6 g of sample in the first container. Once the container has sufficient material, place in the drying oven.

Continue the entire procedure to fill a second sample container with sufficient material (i.e. at least 6 g of sample). Once this second container is filled, place in the drying oven.

Checklist

☐ Obtain two sample containers with soil material that just crumbles at or before it reaches a thread diameter of 3.2 mm

☐ Weigh each sample container and record the weight

☐ Place sample containers in drying oven

4.4.3 Analysis

The analysis portion almost doesn't deserve its own section given how simple it is. You are going to determine the moisture content of your two sample containers from the as-is and oven dry weights. However, per ASTM D4318 §18.1, you will only report the percentage to the nearest whole number. This number is your plastic limit, *PL*, and is usually reported as a dimensionless number.

The reason you had two sample containers is to check if you truly achieved the plastic limit state. ASTM D4318 §18.2 describes how to evaluate the single-operator precision for your data. You will need the soil type of the material which will be provided during the laboratory exercise. Then you will look in column 5 of Table 2 within ASTM D4318. This column gives you the acceptable range that any two test results can have. If we look at a CH material, we can see that our *PL* results can only range by 1. That is, two measured values of 13 and 14 are acceptable but two measured values of 13 and 15 would be rejected and the test would have to be run again.

Checklist

☐ Calculate plastic limit

☐ Check for single-operator repeatability

4.5 Summary

You have successfully run a plastic limit test. This plastic limit, combined with the liquid limit described in the next section, provides geotechnical engineers with critical information about the behavior of a soil and aids in the classification process. While the test procedure may seem trivial, it is surprisingly repeatable for most soil types.

4.6 Liquid Limit Test

The liquid limit test is another relatively simple procedure to evaluate the point at which the soil sample transitions from a plastic state to a semi-liquid state. A plastic soil sample is placed in a brass bowl called a Casagrande cup. It is then grooved and dropped repeatedly until the groove closes back up. The number of drops correlates to the liquid limit through a set of calculations. We are trying to capture the transition to a semi-liquid state, which is an arbitrary state. It is not a free flowing liquid yet it is not plastic enough to retain its shape upon a load. Going back to our Play-Doh® example, think of it as the transition from new Play-Doh® (i.e. plastic) to Play-Doh® with extra water added (i.e. semi-liquid). Similar to the plastic limit test, the liquid limit test cannot be used on cohesionless soils such as sands.

4.7 Objectives

At the completion of this lab exercise, you will have satisfied the following objectives:

1. Perform a series of liquid limit tests on a silty-clayey soil material
2. Perform a calculations necessary to determine the liquid limit

4.8 Learning Outcomes

At the completion of this lab exercise, you should be able to:

- understand the difference between plastic and semi-liquid states of a soil material
- perform calculations necessary to determine the liquid limit of a soil material

4.9 Procedure

The liquid limit testing procedure is divided into three parts: preparation, execution, and analysis. Using the specified Casagrande cup setup (Fig. 17), the sample soil material will be grooved and then dropped at three different moisture contents. The number of drops, or blows, that it takes for the groove in the soil to close will be recorded. The corresponding moisture content will be measured. The liquid limit can then be calculated from the results of the tests.

Fig. 17. Example of a manually operated Casagrande cup. The crank is rotated counter-clockwise to lift and drop the brass bowl to impart a small but repeatable impact force into the specimen.

4.9.1 Preparation

There are two critical pieces of equipment necessary to complete the liquid limit test: a grooving tool (Fig. 18) and a hand-operated Casagrande cup setup. There are mechanical Casagrande cup setups that perform the test automatically, however for this exercise you will use the hand-operated version. While ASTM D4318 §10 requires the verification of the Casagrande cup assembly, you may assume the assembly provided to you has been verified. Additionally, you will need three sample containers so that the moisture content can be determined.

Fig. 18. Example of plastic and metal grooving tools for use in the Casagrande cup. There is a different type of grooving tool that can also be used but will not be utilized for this laboratory exercise.

The most difficult part of the preparation is the soil sampling process. You want to start with the soil sample at a moisture state that will close the gap with 25 to 35 blows. For someone with no experience with this test, it can be nearly impossible to estimate this and a significant amount of time will be wasted attempting to achieve the correct starting moisture state. A previously prepared sample will be provided for you to start with.

You will be performing three tests at different moisture contents. To determine the precise moisture content for each test, the sample will be oven dried in a container. Measure the empty weights of the three sample containers and label them with sufficient detail that you can identify them at a later time.

Checklist

☐ Obtain liquid limit bowl apparatus and grooving tool

☐ Obtain previously prepared soil

☐ Obtain the empty weight of the three sample containers and label them

4.9.2 Execution

We will be performing the multi-point method as outlined in ASTM D4318 §12. You will take a sample of the previously prepared soil and place it into the Casagrande cup. We are looking to achieve a horizontal surface, with respect to the ground, noting that the bowl sits at an angle. The depth at the deepest point in the bowl should be approximately 10 mm. Observe the surface for any air bubbles and attempt to eliminate them with as few pats as possible. If the sample is patted excessively, it will start to bleed water and will significantly affect the test result.

Once the soil pat is ready, groove it down the center with the grooving tool. The beveled edge of the tool should face you as you start at the back of the sample and pull towards you. The tool should be held perpendicular the entire time noting that the bowl is at an angle different than the table. It should take only one attempt to groove the soil pat. Do not groove the same sample multiple times as this may cause bleed water to form.

After the groove is formed, rotate the crank on the bowl at a rate of approximately 2 revolutions per second. Be sure to count the number of rotations, or drops, applied. Once the groove has closed to a length of approximately 13 mm, stop the test and record the number of drops.

Obtain a strip of the sample that includes a portion of the grooved section. Place in the sample container and record the weight. This sample will be oven dried overnight and you will be provided with the data at a later time.

Depending on the number of drops it took the first specimen to close, the remaining two samples may need additional water or to be dried. Ideally, the three tests would have a sample from each of the following ranges: 25–35, 20–30, and 15–25. As the water content increases, the number of drops required to close the groove decreases. So, if your first sample took 27 drops to close the groove, your next two tests should have increasing water contents. You typically would vary the water content by a single percent. So, if your first sample had a starting water content of 62%, your next two samples should probably have water contents of 63% and 64%.

You will repeat the bowl drop procedure for the remaining two moisture contents. Remember to obtain a sample of each specimen in order to determine the exact moisture content.

Checklist

- ☐ Record the number of drops required to close the gap of the three samples
- ☐ Record the estimated moisture contents for all three samples
- ☐ Record the weight of the obtained sample from each test run prior to oven drying

4.9.3 Analysis

The analysis phase is similar to the plastic limit test in that it is straightforward. However, a chart is involved in the analysis of liquid limit data. Once you have obtained your oven dry weight for the three samples, calculate the actual moisture content for each sample.

You will then plot your calculated moisture content versus number of drops required to close the groove. However, the x-axis (i.e. number of drops) should be plotted on a log scale, but the moisture content plotted on a arithmetical (i.e. linear) scale. Once plotted, apply a linear fit. The liquid limit is taken as the moisture content necessary to close the groove with exactly 25 drops. We round the moisture content to the nearest whole percent. For the example below (Fig. 19), the liquid limit would be 44.

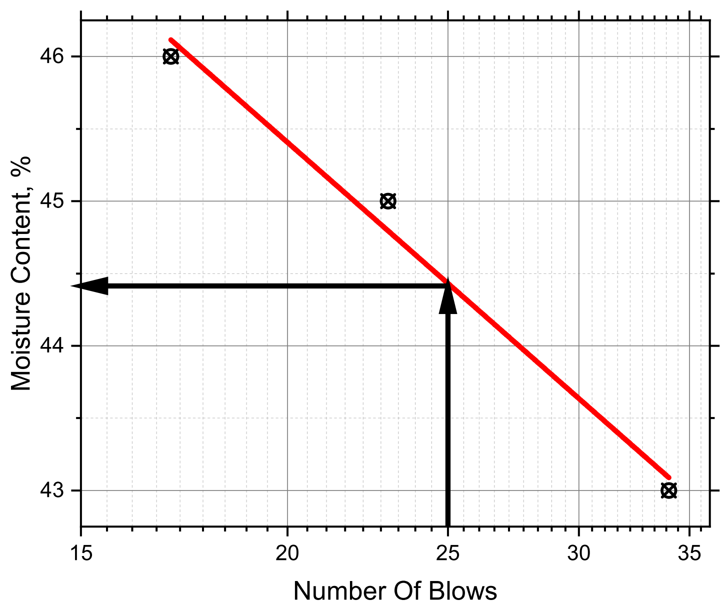

Fig. 19. Example of liquid limit plot. The x-axis is plotted on a log scale while the y-axis is plotted on a arithmetical (i.e. linear) scale. The liquid limit is taken as the moisture content necessary to close the groove with exactly 25 drops.

Checklist

☐ Calculate the true moisture contents for the three samples

☐ Plot the corresponding data

☐ Determine the liquid limit to the nearest whole percent

4.10 Summary

You have successfully run a liquid limit test. The liquid limit, combined with the plastic limit previously described, provides geotechnical engineers with critical information about the behavior of a soil and aids in the classification process. While the test procedure may seem “weird” or unusual, it is surprisingly repeatable for most soil types.

5. Compaction

Abstract

Compaction of soils is an important part of many civil engineering projects. It is not usually sufficient to compact a soil to a point at which it looks good. We need to understand how compacted our soil can be so that we can perform design calculations. Additionally, we need to know the maximum possible compaction we can achieve with a soil so that we can check compaction in the field during the construction process. The most common method to evaluate the compactability of a soil is called the Proctor method, named after R.R. Proctor who developed the method in 1933. The testing procedure involves compacting a series of soil samples at increasing moisture contents. The resulting data is plotted and the maximum unit weight can be determined. Associated with this parameter is the optimum moisture content.

Required Standards

The following specifications are required to complete this laboratory exercise:

ASTM D698 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3))

The following specifications are optional, but they are listed here in the event more information is needed to complete the laboratory exercise:

ASTM D6026 Standard Practice for Using Significant Digits in Geotechnical Data

5.1 Proctor

The standard Proctor test has been around for nearly 80 years. It is a reliable workhorse test method that provides valuable data for design and construction. A known weight is repeatedly dropped from a constant height to compact a soil specimen in a cylindrical mold. The mass and volume of the soil are determined and the resulting unit weight can be calculated. This is done for a series of moisture contents to establish what is called the moisture-density curve.

The standard Proctor test, ASTM D698, simulates the compaction achieved with relatively small compaction equipment, such as hand tampers, vibratory walk-behind compactors, jumping jacks, etc. Modern virbatory roller compactors can put significant compactive effort into the soil. There is a modified Proctor test, ASTM D1557, which better simulates the compaction seen when using large compaction equipment. The primary difference between the two methods is the weight and height of the drop for the compaction (Fig. 20). The remainder of the procedure is nearly identical.

Fig. 20. Comparison between the standard proctor hammer (background) and the modified proctor hammer (foreground).

5.2 Objectives

At the completion of this lab exercise, you will have satisfied the following objectives:

1. Perform a series of compaction tests using the standard Proctor method
2. Perform calculations necessary to create a moisture-density curve

5.3 Learning Outcomes

At the completion of this lab exercise, you should be able to:

- understand what the laboratory compaction process represents
- perform calculations necessary to determine the maximum dry unit weight and optimum moisture content of a soil sample
- understand how to interpret information from a moisture-density curve

5.4 Procedure

The standard Proctor test procedure is divided into three parts: preparation, execution, and analysis. While the test can be run on moist and dry samples, it is preferred that the test be run on moist samples (ASTM D698 §10.2). Additionally, samples should not be reused for further compaction per ASTM D698 §10.1.1. You will be provided with sufficient moist material that you will be able to run three compaction tests without needing to reuse the soil.

5.4.1 Preparation

You will need three pieces of equipment for this procedure: compaction hammer, compaction mold, three sample containers, and a scale. For the standard Proctor method, the hammer is 5.5 lbs. Since the soil is relatively fine, a 4-inch diameter mold is appropriate (Fig. 21).

Fig. 21. Example of a 4-inch diameter proctor mold. The taller piece goes on first followed by the shorter piece.

You will need to determine the empty weight of the compaction mold. While we can remove the sample from the mold most of the time, we sometimes lose too much material. We will obtain the weight of the compacted soil while still in the mold and will need to subtract the weight of the mold from the measurement. You will be provided with the volume of the mold for use in calculations during the analysis portion.

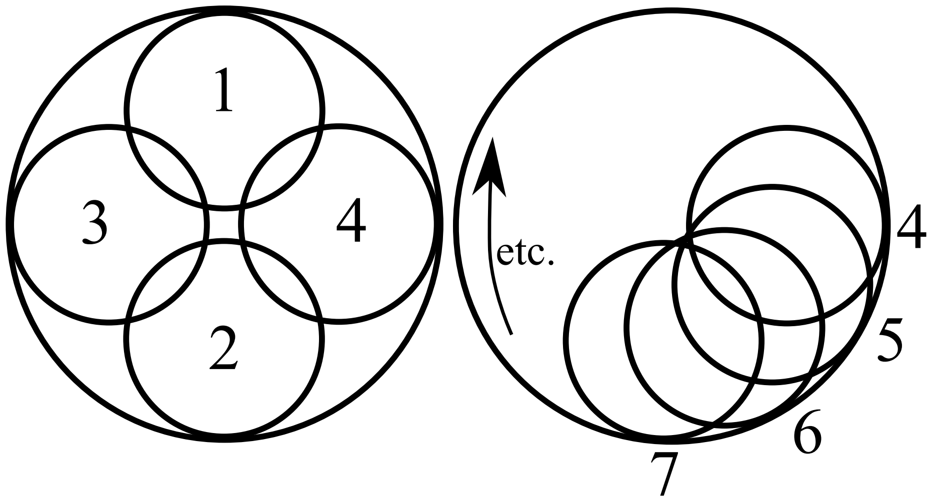

Fig. 22. Schematic of compaction pattern required in ASTM D698. The four quadrants are first compacted with one blow each followed by circular compaction around the perimeter of the circle.

Checklist

☐ Obtain compaction hammer and compaction mold

☐ Obtain empty weight of compaction mold

☐ Obtain diameter and height measurements of the compaction mold. Do not include the upper ring in your measurements.

☐ Obtain the weights of the three sample containers

5.4.2 Execution

The execution process is straightforward. You will compact the soil in the mold using three layers of equal height. Each layer is compacted with 25 drops of the hammer. It takes some experience to know how much soil to add for each layer, especially the first layer, so that you end up with three equal layers. It is important to begin the compaction of each layer properly in terms of the pattern (Fig. 22). The four quadrants will first be compacted followed by a blows that go in a circular pattern around the mold until a total count of 25 blows has been achieved.

Occasionally, an uneven surface may develop during the compaction process. While the pattern is explicitly stated in ASTM D698, there is a provision in §10.4.5 to allow the operator to exercise professional judgement to ensure the specimen is compacted evenly. It is important that each layer be relatively even, especially the top layer. ASTM D698

§10.4.3 states that the final compacted layer height can exceed the top of the mold by a maximum of 0.25 inches or the entire test is discarded. Experience greatly increases the chance that the final height is within this tolerance.

After compaction of the top layer is complete, you will trim the excess height with a knife or similar straightedge. If there are any voids or "potholes" present in the top surface, you may fill those in with the remaining soil and use the straightedge to again strike off the top surface. Then you will obtain the weight of the compacted soil within the mold.

To determine the moisture content, we will take the compacted specimen out of the mold and oven dry it. Place as much as the sample as you can into the sample container weigh the moist soil sample. The specimen container will then be placed into a drying oven and you will be provided with the oven dry weights the next day. Ensure your specimen containers are properly labeled.

The next two compactions will be done in an identical manner except with additional water added to the soil specimens. For your second specimen, weigh out approximately 3 kg of moist soil. Then, calculate the amount of water you would need to add to your measured soil mass to increase the moisture content about 2%. That is, if the moist soil starts at a moisture content of 5%, how much water is needed to bring that moisture content to 7%. Recall that the moisture content, w, is given by Eq. 5

$$w = \frac{M_w}{M_s} = \frac{M_w}{M_t - M_w} \tag{5}$$

where M_w is the mass of water, M_s is the oven dry mass, and M_t is the moist mass. However, we do not have the starting moisture content from the first compaction specimen yet. We need to exercise some engineering judgement. Estimate the moisture content of the starting sample! It is probably somewhere between 4% and 7%. So if we take our assumed moisture content, we can calculate the expected oven dry mass and then determine how much additional water is needed to increase the moisture content by 2%.

Example

For example, say we have 1 kg of a moist soil sample and we assume the moisture content to be 3%. We want our next sample to be at 5% so we need to determine how much additional water to add to go from 3% to 5%. From Eq. 5, we can calculate[a] that a 1 kg moist sample at 3% moisture has a water mass of 29.1 g and a oven dry mass of 970.9 g. So, the total amount of water to add to 970.9 g of oven dry soil to bring the moisture content up to 5% is 48.5 g. However, our actual sample already has 29.1 g of water in it, so we just need to add 19.4 g of additional water to go from 3% moisture to 5% moisture.

[a] You will have to rearrange the equation to perform the calculation!

You will compact this second sample, with the additional 2% moisture, the same way as the first sample. Be sure that that drying container is properly labeled. Your third sample will be compacted with an additional 2% moisture from the second sample (or 4% moisture from the first sample). Again, ensure that your drying container is properly labeled.

You will receive the oven dry weights for all three samples the following day. It is very likely that your assumed moisture content will be off, but that is okay! Just ensure that when you perform the analysis, you use the actual moisture contents, not your assumed values.

Checklist

☐ Compact three soil specimens at three different moisture contents. Be sure to record estimated moisture contents.

☐ Weigh each sample container, first empty, and then with the moist samples, and record both weights

☐ Place sample containers in drying oven

5.4.3 Analysis

The calculations for the various unit weights and moisture content are relatively straightforward and outlined in ASTM D698 §11. You will first need to calculate the three moisture contents, w, from your moist and oven dry sample weights[13]. We start with ASTM D698 §11.2.2.1 to calculate the moist density. Pay careful attention to the units! The dry density is calculated in ASTM D698 §11.2.2.2 with the dry unit weight calculated in ASTM D698 §11.2.2.3. It is this dry unit weight that we are after.

Once we calculate the three dry unit weights for our compaction samples, we can plot them versus the moisture content. This plot is our moisture-density curve. This is one of the only times in civil engineering where it is acceptable to use the smooth curve option in Microsoft Excel®. At this point, it would be ideal if we see some sort of upside-down parabola, similar to the example in ASTM D698. The peak of the parabola is our maximum dry unit weight, sometimes called maximum dry density and abbreviated MDD. At this maximum dry unit weight, we can also determine the moisture content. This moisture content is our optimum moisture content (OMC). This tells us that if we had this soil at a moisture content equal to OMC, we would get the maximum possible compaction out of it.

The scale for both the x- and y-axis is important in these types of plots. ASTM D698 §11.3.1 outlines the proper scale to use. One reason to keep the scales consistent is so that the shapes of different soil compaction results can all be compared in the same manner. Sometimes a elongated scale provides a misleading picture of the compaction behavior of the soil and makes any type of comparison difficult.

[13]This is the only calculation not shown as an equation in ASTM D698 as it refers the reader to D2216. However, you know how to calculate moisture content!

There is another line we can plot on our chart to check the reasonableness of the numbers we calculated. There is a point for each moisture content that all the air will be removed from the sample. This would give us the maximum theoretical compaction for the soil at each moisture content. The reason we should never cross this line, sometimes called the zero air void line or 100% saturation line, is because we cannot have negative air in our sample! The equation for this line is given in ASTM D698 §11.4. It does rely on an accurate value for the specific gravity of the solids. For purposes of this laboratory exercise, assume G_s is 2.75. You can plot the line with your moisture-density curve to check the reasonableness of your data.

Checklist

☐ Calculate true moisture contents for the three compaction specimens

☐ Calculate densities and unit weight

☐ Plot the moisture density curve

☐ Plot the zero air void line

5.5 Summary

You have successfully run a standard Proctor test. As you likely noticed, the process is relatively straightforward, albeit time-consuming. This is a routine test that is run on nearly every type of civil engineering project when soil is disturbed or manipulated. The maximum dry unit weight is used in numerous design calculations to determine bearing capacity, percent compaction, and pavement structural layer capacity among other factors.

6. Sand Cone

Abstract

The evaluation of compaction in the field is a critical component to many construction processes. There are numerous technologies available to assess the *in-situ* density of soils including, but not limited to sand cone, balloon, nuclear density gauge, and others. Out of these, the sand cone is the simplest, and perhaps oldest, test method. All that is required is for a hole to be dug on the jobsite. This hole is then filled with sand of known density. By measuring the weight of sand required to fill the hole, the volume can be easily calculate using the sand density. Coupled with the known weight of soil that was removed from the hole at the time of digging, the density of the in-situ soil can be calculated.

Required Standards

The following specifications are required to complete this laboratory exercise:
ASTM D1556 Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method

The following specifications are optional, but they are listed here in the event more information is needed to complete the laboratory exercise:
ASTM D6026 Standard Practice for Using Significant Digits in Geotechnical Data

6.1 Introduction

The sand cone test has been around for over 60 years. It is a reliable and straightforward method to measure unit weight in the field. This is an in-situ[14] test method. While not a common test nowadays, as there are faster test methods available to determine the unit weight of a soil in the field, the sand cone remains a practical method that has no moving parts, batteries, or radioactive sources to maintain. Additionally, it is easy to see visually what is being measured.

6.2 Objectives

At the completion of this lab exercise, you will have satisfied the following objectives:

1. Perform a calibration procedure for the sand cone equipment
2. Perform a field unit weight measurement using the sand cone method
3. Perform calculations necessary to determine the field unit weight

6.3 Learning Outcomes

At the completion of this lab exercise, you should be able to:

- understand an ASTM calibration process
- perform calculations necessary to determine the field unit weight from sand cone data
- understand the concept of compaction percentage

[14]This means "in place" or at the original location, that is, not bringing it back to the lab.

6.4 Procedure

The sand cone test procedure is divided into four parts: calibration, preparation, execution, and analysis. ASTM D1556 will be used for the calibration and procedure methods. Up to this point, we have largely ignored the calibration procedures in ASTM standards for our test methods. However, in the case of the sand cone test, it is extremely important and is done more often than with other testing procedures. The calibration will take place in the laboratory while the actual measurement will be conducted in the field.

6.4.1 Calibration

There are two steps to the calibration process but you will only be conducting the first step. The second step is described in ASTM D1556 §A.2 and determines the unit weight of the sand used for the sand cone. This unit weight will be provided to you. You will generally follow the steps outlined in ASTM D1556 §A.1. There are two methods listed but they are nearly identical. The second method simply outlines a procedure for multiple sand cone sets.

Following the procedures outlined for Method A in ASTM D1556 §A1.2.3, you will set the base plate on the laboratory table and then weigh the sand cone apparatus. Then, place the sand cone in the base plate and open the valve and allow sand to fill the cone portion and the gap between the cone and table. After the sand stops flowing, you will close the valve and slowly remove the cone. You will then weigh the sand cone apparatus (which now has less sand in it). Finally, you will carefully scoop/sweep the sand into a container for reuse[15]. Using the provided unit weight of the sand, you can easily calculate the volume of the cone and gap by using the difference in weights. This value will be your cone correction factor.

6.4.2 Preparation

You will need five pieces of equipment for this procedure: sand cone apparatus (Fig. 23, base plate, scoop, sample container, and a scale[16]. Ensure the sand cone apparatus is filled with enough sand and obtain the filled weight of the apparatus. Finally, obtain the empty weight of the sample container.

[15]ASTM D1556 generally discourages reuse of the sand but we will be careful not to contaminate it
[16]We will not bring this into the field; we will bring the soil sample back to the lab to weigh.

Fig. 23. Assembled sand cone apparatus sitting on a base plate.

Checklist

- ☐ Obtain sand cone apparatus and base plate
- ☐ Obtain scoop and sample container
- ☐ Obtain the filled weight of the apparatus
- ☐ Obtain the empty weight of the sample container

6.4.3 Execution

The execution process is straightforward. You will go to the designated site and set your base plate down. Hammer the soil stakes in to stabilize the base plate while you excavate the soil with the scoop. It is critical that as you scoop soil out to form a hole that you do not lose any soil. All of the excavated soil should be placed in the sample container and sealed until you can obtain the in-situ mass back in the lab.

The minimum size of the hole is listed in ASTM D1556 §7.1.5 and is dependent on the gradation of the soil you are testing. Essentially, we want a hole big enough to reduce error but smaller than the volume of sand in our sand cone. The shape of the hole you dig is also important as we need the sand to freely flow and fill in the hole. We cannot have overhangs or crevices that the sand would not easily reach (Fig. 24).

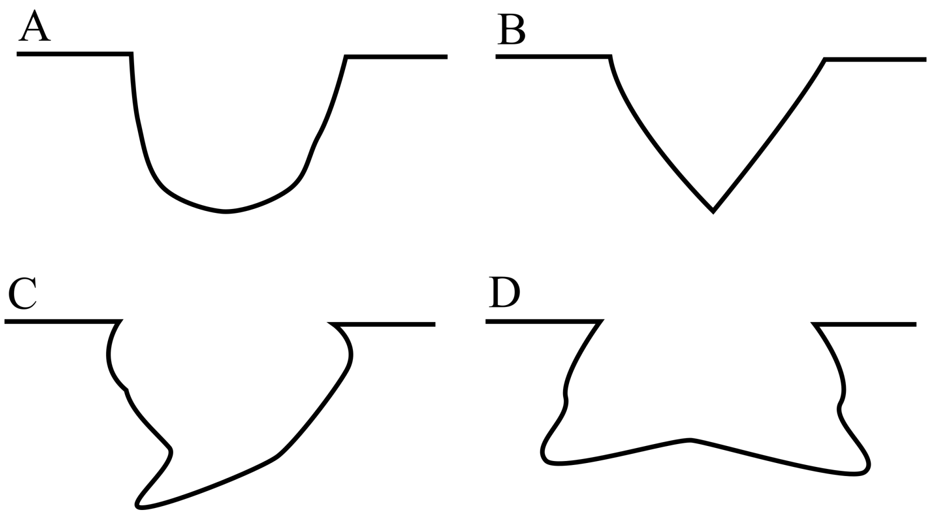

Fig. 24. Example hole cross sections with (A) and (B) indicating good holes and (C) and (D) indicating poor holes.

After you have collected all of the loose soil in the sample container, seal it to prevent moisture loss while you complete the sand cone test. Place the sand cone apparatus on top of the base plate and ensure it is fully seated. Open the valve and allow the sand to fill the entire volume. Once the sand has stopped flowing, close the valve and slowly remove the sand cone apparatus. As previously mentioned, we generally cannot reuse the sand because it becomes contaminated with the soil we are testing on. Thus, you will leave the sand in the hole and remove the stakes and base plate for transport back to the lab.

Once back in the lab, obtain the weights of the soil sample and the emptied sand cone apparatus. Your soil sample will be oven dried and the resulting oven dry mass will be provided to you. Ensure your sample container is sufficiently labeled for later identification.

Checklist

☐ Excavate a hole and collect all soil in a sealed container

☐ Weigh sample container with moist soil sample

☐ Weigh emptied sand cone apparatus

☐ Place sample container in drying oven

6.4.4 Analysis

The calculations for determining the densities is straightforward and clearly outlined in ASTM D1556 §8. We first calculate the volume of the hole. This is done by taking the difference of the starting weight and ending weight of the sand cone apparatus, subtracting the calibration value determined earlier, and then dividing by the unit weight of the sand. Keep track of your units!

After the volume is known, the calculation of both wet and dry densities is easily performed. It is simply the measured wet or dry weight of the soil removed from the hole divided by the volume of the hole. The number of decimal places we can report to is outlined in ASTM D1556 §9.4.

The last thing we need to do with our data is to see at what "percent compaction" we were at in the field. When we run a density check in the field, we are trying to see if we have reached some target compaction. It is most commonly reported as a percentage of the maximum dry density, which was determined in the lab from the standard Proctor test following ASTM D698.

Example

For example, let's assume our specimen has a maximum dry density, determined from the standard Proctor, of 125 lbs/ft^3. If the results of our sand cone test determine that the in-situ dry density is 121 lbs/ft^3, we have obtained 96.8% compaction. The required percentage depends on the project details, but minimum compaction values of 90% or 95% are most common.

Checklist

- ☐ Calculate the volume of the hole
- ☐ Measure dry mass of soil removed
- ☐ Calculate in-situ wet density
- ☐ Calculate in-situ dry density
- ☐ Calculate in-situ percent compaction

6.5 Summary

You have successfully run a sand cone test. As you likely noticed, the process is relatively straightforward and easy to run. This test used to be a routine test but was surpassed by faster and more accurate methods such as nuclear density gauges. Even though not as common, the sand cone method provides a good opportunity to visually observe how the compaction can be measured and more importantly, the size of the measurement.

7. Permeability

Abstract

There are numerous methods to evaluate how water flows through soils. There is no single method that is the best for any situation. Residential projects will typically specify a percolation or double ring infiltration test while an industrial project, concerned about hazardous waste transport, may specify a permeability test. The previously mentioned percolation, or perc, test and double ring infiltration test are field tests (performed "in-situ," that is on in-place soils) that require extensive setup and take a substantial amount of time to run. Conversely, the permeability test is a laboratory test that can be performed on either undisturbed or remolded samples and which is, for some soils, relatively fast. If you have experience with fluids or hydrology, you might recall you can have a constant head or falling head situation for water flow. This laboratory exercise will utilize the constant head permeability method to evaluate our soil samples.

Required Standards

The following specifications are required to complete this laboratory exercise:
ASTM D2434 Standard Test Method for Permeability of Granular Soils (Constant Head)

The following specifications are optional, but they are listed here in the event more information is needed to complete the laboratory exercise:
ASTM D6026 Standard Practice for Using Significant Digits in Geotechnical Data

7.1 Introduction

The constant-head permeability test method has been around for over 50 years. It is one method, among many, that can describe the water transport behavior of a soil. This test uses gravity and water flow from one height to another to force water through the soil sample. By measuring the head of the in-flowing and out-flowing water and the flow rate of the water through the sample when this head is applied, we can establish the flow rate properties of the soil sample. This test can be performed using either an "undisturbed" sample (like a Shelby Tube sample) or a "remolded" sample which is formed from a disturbed soil sample (like a bulk sample). Since soils in the field can be compacted to different amounts, the standard recommends running the test at several relative densities (typically by compacting soil from bulk samples to varying degrees and extruding a sample from that for the test). For our purposes, we will consider a completely uncompacted sample (i.e. the soil poured into the test chamber without the application of any compactive energy). Additionally, this test method is typically used on granular soils which have less than 10% passing the #200 sieve. If too many fines are present, the test is difficult to perform as the flow rates are extremely small.

7.2 Objectives

At the completion of this lab exercise, you will have satisfied the following objectives:

1. Perform a series of constant-head permeability measurements
2. Perform calculations necessary to determine the temperature-corrected permeability of a soil sample

7.3 Learning Outcomes

At the completion of this lab exercise, you should be able to:

- understand permeability, hydraulic gradient, and flow rates of a soil and how the terms are interconnected
- perform calculations necessary to determine the permeability of a soil at any temperature

7.4 Procedure

The constant-head permeability test procedure is divided into three parts: preparation, execution, and analysis. In practice, ASTM D2434 provides the standard specifications for performing this test. For our purposes, we will be deviating from the specifications presented in this standard based on the type of test equipment that we have available. The key difference is that, in our procedures, the head difference will be measured based on the geometry of our test apparatus and its in-flow and out-flow point rather than measuring the head using a set of manometers as specified in ASTM D2434. The procedure requires one piece of equipment that should be provided by you, the student: a stopwatch (i.e. use an app on your cellphone).

7.4.1 Preparation

You will need the following equipment for this procedure: the permeameter (including the three O-rings, both halves of the sample container, two porous stones, spring, permeameter frame with ruler, and upper inlet funnel), a scoop and small funnel, a graduated cylinder with a capacity of 100 mL, a water source, and a series of tubing sections. The permeameter with all associated parts is shown in Fig. 25.

Since we are performing a constant-head measurement and not a falling-head measurement, the calculation of the permeability coefficient, k, is straightforward and shown in Eq. (6):

$$k = \frac{QL}{Aht} \tag{6}$$

where:

$Q =$ volume of outflow for time t

$L =$ length of the soil sample

$A =$ cross-sectional area of the sample

$h =$ head difference between the in-flow and out-flow points

$t =$ time of outflow measured

As part of the preparation, you should carefully measure the inside diameter of the sample chamber, the height (length) of the soil sample between the two porous stones. These measurements give us what we need to calculate A and L. You should also measure the distance between the side outlet of the upper funnel and the inlet port at the bottom of the sample as well as the distance from the outlet port at the top of the sample and the inlet port at the bottom of the sample. The difference between these two vertical distances is h. By obtaining these measurements before we even start the test, we do not have to worry about remembering to record those measurements later.

Fig. 25. Permeameter setup used in lab. Note the water tubing is omitted for clarity.

Once you have collected all parts of the permeameter and the other listed items, you can then place the sand into the sample chamber and assemble the chamber. First, place one of the porous stones in the bottom of the sample chamber. Then place the soil using the scoop and small funnel. Scoop some of the sand and pour it through the small funnel, using the funnel to distribute the sand evenly around the chamber. Once your sand is filled up near the top of the bottom half of the sample chamber, place an O-ring and the top half of the sample chamber. Continue placing sand until you are near the top of the sample chamber, then place the second porous stone, the spring, and the top lid of the sample chamber. Hook up the tubing as shown in the figure and you are ready to begin your test.

Checklist

☐ Obtain permeameter, including all associated parts

☐ Obtain sand sample, scoop, and small funnel to fill the sample chamber

☐ Identify water source and setup apparatus adjacent to it

☐ Measure the height of the upper funnel side spout and outlet port at top of the sample chamber

☐ Measure the diameter and length of the sample chamber

☐ Assemble the sample chamber and place the sand sample

☐ Attach tubing sections

7.4.2 Execution

Once your device is set up, the execution process is straightforward. Connect a section of tubing to the sink faucet and secure the the other end of the tubing so that it routes water into the upper funnel. Connect another piece of tubing to the side outlet of the funnel and place the other end of that tubing into the sink basin. For now, place the open end of the hose that is attached to the outlet port on the sample chamber into the sink basin as well. Your apparatus should now be setup so that water will flow into the upper funnel, down the tubing to the bottom of the sample chamber, through the sample, and out the top of the sample chamber. Turn the water on so that water begins to fill the upper funnel. You want to adjust the flow rate so that the upper funnel is constantly filled up to the side outlet, but that it does not exceed this level. Water will flow out of the side outlet of the upper funnel to maintain the water level in the upper funnel. Allow the water to flow through the system until the sample is saturated and the water begins to flow out of the top of the sample chamber.

Now you will take the flow measurements to be used in your analysis. Get your timer ready, then place the open end of the tube that comes from the top of the sample chamber into the graduated cylinder and start the timer. Stop the timer when the water level in the graduated cylinder reaches 100 mL. Record the time that this takes. From this you will gain the flow rate in terms of mL/sec or cm^3/sec.

Checklist

☐ Attach tubing to the sink faucet and place open end in the upper funnel

☐ Attach tubing to the outlet of the upper funnel and route this to the sink basin

☐ Attach tubing to the top port outlet of the sample chamber

☐ Turn on water to fill the upper funnel and maintain a steady level

☐ Allow water to saturate the sample and flow from top of sample chamber

☐ Measure the time that it takes to fill the 100 mL graduated cylinder from the tubing coming out of the top of the sample chamber

7.4.3 Analysis

The objective of your analysis is to obtain the coefficient of permeability (k) for your soil sample. This is easily done using Eq. (6), which is provided in the Preparation section of this manual and ASTM D2434 §8.1. We can define the variables in terms specific to our test measurements:

$Q =$ 100 mL (the volume of our graduated cylinder)

$L =$ length of the soil sample, measured between the two porous stones

$A =$ cross-sectional area of the sample, calculated based on the measured diameter of the sample chamber

$h =$ the vertical distance between the side outflow port of the upper funnel and the outlet port on the top of the sample chamber

$t =$ time to fill the graduated cylinder in seconds

Using this equation and the values obtained from the test, you should be able to compute the k value for the soil in units of cm/sec.

Checklist

☐ Calculate the cross-sectional area of the sample

☐ Calculate the head across the sample (the difference between the height of the side port of the upper funnel and the height of the outlet port at the top of the sample chamber)

☐ Calculate the coefficient of permeability

7.5 Summary

You have successfully run a laboratory permeability test. This process is similar to the more rigorous standardized version of the test in ASTM D2434, and as such you should now have a feel for the general concepts behind laboratory permeability tests. You also should now have an idea of how water flows through soils and what values are related by the coefficient of permeability.

8. Intermediate Deliverable Content Requirements

This section will outline the absolute minimum required data necessary for your various intermediate deliverables. The key point is to include all data necessary to recreate your calculations. If you only provide your final numbers, there is no way to verify if you were calculating the properties correctly. Each step of the calculation process should be shown but you do not need to explicitly show equations. The equations you are using are implied by the fact you are performing a specific and standardized test method.

8.1 Visual Classification

☐ Professional formatting with no spelling, grammatical, or typographical errors.

☐ Date, time, sample type, and location information.

☐ Sample ID for each specimen.

☐ The soil description including all relevant items for each soil sample as demonstrated in §1.4.3. You may have more than one description per page so long as the formatting is clear and professional.

☐ A brief (3 to 5 sentences) description of your process and observations, outlining what you observed and what this meant for your description (e.g. "When I attempted to roll the fine-grained soil to form a thread, it crumbled immediately indicating that the soil was a silt").

8.2 Sieve Analysis and Hydrometer

☐ Professional formatting with no spelling, grammatical, or typographical errors.

☐ Date, time, sample type, and location information.

☐ Sample ID for each specimen.

☐ Separate page for each specimen. Do not present more than one sample on a page or you will lose all points for the deliverable.

☐ All columns of data for calculating a sieve analysis (i.e. sieve numbers, sizes, weights, etc). Each column should be clearly labeled following appropriate guidance for units.

☐ Starting and ending total weight of each material analyzed.

☐ Table of hydrometer data similar to the lower half of Figure X1.1 in ASTM D7928. This will require you to look up the table in the ASTM standard.

☐ Graph of each complete gradation (i.e. both sieve analysis and hydrometer analysis results combined on a single graph. Remember that gradations are presented with the particle diameter axis on a log-scale.

☐ As appropriate, calculated fineness modulus.

☐ Location to present numerical Atterberg Limits[17].

☐ Determined USCS and AASHTO soil classification[18].

[17] You will not have this data in time for the intermediate deliverable but will when you submit the final geotechnical report.

[18] Again, you will not be able to do this for all samples due to the absence of Atterberg Limits. Just leave a space if you cannot classify the soil at the time of submission.

8.3 Atterberg Limits

☐ Professional formatting with no spelling, grammatical, or typographical errors.

☐ Date, time, sample type, and location information.

☐ Sample ID for each specimen.

☐ Plastic limit, liquid limit, and plasticity index[19].

☐ Show your work by looking at Appendix D for guidance. At a minimum, you should have:

- ☐ empty (i.e. tare) weight of the sample cans
- ☐ weight of moist soil
- ☐ weight of dry soil
- ☐ moisture content of soil
- ☐ number of blows associated with the moisture content
- ☐ chart showing calculation of LL value, as described in Fig. 19

[19]This calculation was covered in lecture and is simply the liquid limit minus the plastic limit

8.4 Compaction

☐ Professional formatting with no spelling, grammatical, or typographical errors.

☐ Date, time, sample type, and location information.

☐ Sample ID for each specimen.

☐ Show your work by looking at Appendix E for guidance. At a minimum, you should have:

- ☐ height and width of specimen mold
- ☐ volume of specimen mold
- ☐ all masses required to calculate the unit weight and moisture content
- ☐ total, or moist, unit weight for each trial
- ☐ dry unit weight for each trial
- ☐ maximum dry unit weight
- ☐ optimum moisture content

☐ Chart of moisture-density relationship with annotations indicating the maximum dry unit weight.

☐ On the moisture-density chart, plot the zero-air void line using the assumed soil solids specific gravity of 2.75.

8.5 Sand Cone

☐ Professional formatting with no spelling, grammatical, or typographical errors.

☐ Date, time, sample type, and location information.

☐ Calibration data: unit weight of sand cone sand and volume of cone and gap in alignment plate (i.e. calibration factor).

☐ Show your work by looking at Appendix F for guidance. At a minimum, you should have:

- ☐ weight of soil removed from hole
- ☐ starting weight of sand cone apparatus filled with sand
- ☐ ending weight of sand cone apparatus after some sand has been released into the hole
- ☐ volume of hole
- ☐ total unit weight of soil
- ☐ dry unit weight of soil
- ☐ moisture content of soil

☐ Percent compaction (you will need to have already performed your moisture-density calculations from the Standard Proctor laboratory exercise)

8.6 Permeability

☐ Professional formatting with no spelling, grammatical, or typographical errors.

☐ Date, time, sample type, and location information.

☐ Show your work by looking at Appendix G for guidance. At a minimum, you should have:

- ☐ sample height
- ☐ head and cross sectional area
- ☐ unit volume of measure (i.e. 100 mL)
- ☐ time to fill unit measure
- ☐ calculated permeability coefficient
- ☐ average permeability coefficient

9. Intermediate Deliverable Formatting Requirements

This laboratory course will likely be structured unlike anything you have done previously. Each exercise is specifically designed to be a part of a single final report and examples of well formatted documents are provided in the appendices for each exercise.

For each exercise, you should easily be able to fit all the required information on a single page. A significant portion of your grade will come from professional formatting. You will likely spend more time making the page(s) look good than performing the actual calculations and this is okay! Professional engineers will typically use software specifically designed to make nice sheets. However, there are still some firms and engineers that do it manually. Most of the time the entire page is created in MS Excel due to the insane number of rows and columns needed. Some tips are presented below to help you format your document well.

9.1 Decimals

The number one reason for point deductions is absence of leading zeros. It is critically important for technical communications to be as concise and accurate as possible. When there are no leading zeros, the reader may mistaken the decimal for a spot on the page or may miss the decimal completely (Table 7).

Table 7. Examples of values presented without (Column A) and with (Column B) leading zeros.

	Column A	Column B
Property 1	.01	0.01
Property 2	.5	0.5

Another aspect relating to decimals is the consistent use. For example, if you are presenting a list of moisture contents, you need to present them consistently and to the accuracy of the relevant standard (Table 8). Each value, for the same property, cannot have differing precision (i.e. decimal places). This is the second most common point deduction for formatting.

Table 8. Examples of values presented with inconsistent decimal places (Column A) and consistent decimal places (Column B).

	Column A	Column B
Moisture 1	1%	1.0%
Moisture 2	2.3%	2.3%
Moisture 3	3.22%	3.2%
Moisture 4	1.02%	1.0%

The astute reader will note that this very document contains what appears to be a discrepancy in these rules. In Table 1, the number of decimal places is not consistent at all! When we are presenting data that is the same unit (i.e. particle size in mm or in) but the scale ranges over several orders of magnitude (i.e. powers of 10), we have little choice but to change up the decimal places. We could get around this and be explicit by using engineering notation, however for the specific purpose in Table 1, engineering notation would not be ideal.

9.2 Units

All values presented should have units indicated clearly. There are several methods to achieve this based on the specifics of the data being presented (Table 9). The choice of method is usually dictated by the complexity of the information being presented. A general recommendation is to attempt to minimize the amount of text by either using column or row labels.

Table 9. Examples of how to indicate units via a column label (Column A), assigning each value a label (Column B), or indicating via a row label (last row).

	Column A [%]	Column B
Moisture 1	1.0	1.0%
Moisture 2	2.3	2.3%
Moisture 3	3.2	3.2%
Moisture 4, %	1.0	1.0

9.3 Excel Specific Formatting

When building your deliverables in Excel, keep the font size at least 10 pt. Anything smaller does not print well and can become illegible. Similarly, the cell border thicknesses can be customized. You might notice that a lot of the example datasheets make use of several line types. In Excel, you can draw custom borders around any cell quickly and easily to better emphasize portions of your deliverable (Fig. 26). You will lose points if you fail to emphasize portions of your deliverables with different line styles.

Using Excel to create the datasheets can be difficult because the "page" is not shown so it can be unclear as to the bounds of your document. Excel has a function to allow you to edit your spreadsheet while only seeing the printable sections.

1. Create a new spreadsheet or open an existing spreadsheet.
2. Start adding some data[20].
3. Go to View in the ribbon and select Page Break View.

[20]The next step will not work if your spreadsheet is completely blank.

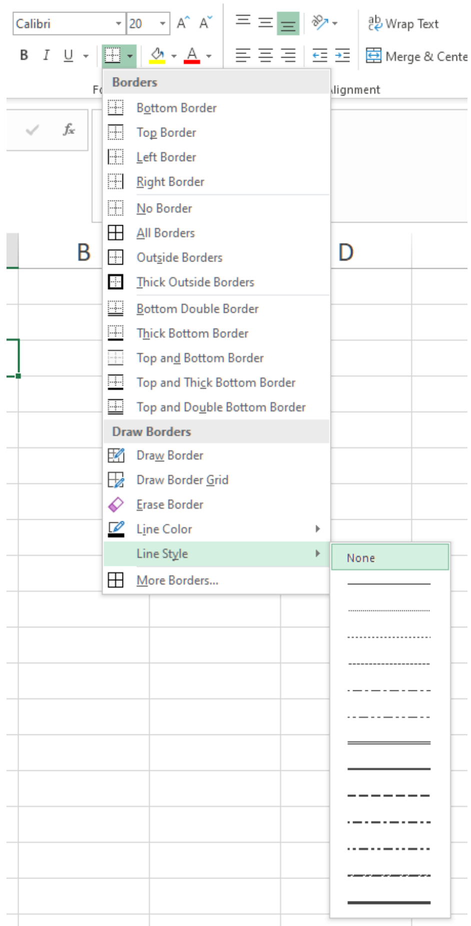

Fig. 26. Screenshot of menu to change line type and color in Excel.

You will be able to see what will be printed on a page and can adjust column widths and row heights to ensure everything is printed properly. Additionally, you can do all your work (i.e. data entry, calculations) in the page view mode so that you can always see if your formatting will work.

10. Geotechnical Report and Formatting Requirements

Abstract

The culmination of a series of laboratory and field tests is a geotechnical report. Most large civil engineering projects cannot begin until an exploratory geotechnical survey of the area is completed. Even small projects like a residential home can require the submission of a preliminary geotechnical report. While there are many different kinds of reports, and usually no standard template to follow, we will consider one general type. The geotechnical report format that will be used will contain seven distinct portions: cover letter, project description and scope, site description overview, testing methodology, subsurface soil conditions, design calculations/recommendations, and raw data. The geotechnical report that you will write will be in response to a client who is planning a single-family residence.

10.1 Objectives

At the completion of this lab exercise, you will have satisfied the following objectives:

1. Develop a geotechnical report from previously calculated/measured values
2. Develop a geotechnical report using data from government sources

10.2 Learning Outcomes

At the completion of this lab exercise, you should be able to:

- understand how to present a large amount of data effectively to a varied audience

10.3 Cover Letter

The cover letter is short and to the point. It will indicate the client, the general work performed, highlight important results[21], and indicate professional review via a physical or digital professional engineering stamp[22]. For small projects, your cover letter, excluding company info and other top matter, may only be three or four sentences. An example cover letter is shown below.

[21] Sometimes, other times it is preferred to leave data out of the cover letter.

[22] Each state is allowed to set criteria for how/where/when/why a document is stamped by a professional engineer. For example, Florida allows for digital stamping but the PDF can not be printed and still considered stamped.

Example

May 7, 2021

Bad Wolf Engineering, INC.
76 Totters Lane
Tuscaloosa, AL 35487

Attn: Ms. Engineer

Re: Geotechnical Report for Engineering Quad Swimming Pool Project

Dear Ms. Engineer,

Very Good Geotechnical Testing, INC. is pleased to submit our geotechnical engineering services report for the construction of a swimming pool in the engineering quad. The scope of our services was outlined in our original proposal.

The following report presents the project information made available to us, our observation of the existing site conditions, the subsurface geotechnical information obtained during this exploration, and our evaluation of subsoil and groundwater conditions. Also included with this report, are the results of our field and laboratory testing. The assessment of site environmental conditions for the presence of pollutants in the soil, rock, and groundwater at this site was not included as a part of our services.

We appreciate the opportunity to provide these services to you. If you have any questions regarding this report or if we may be of further service to you, please do not hesitate to call us.

Sincerely,

Very Good Geotechnical Testing, INC.

10.4 Project Description and Scope

Since the geoetechnical report will be a stamped document and will have legal standing, it is critically important to carefully and accurately identify the project, as you understand it, and the scope of the services you are providing. For example, if the client stated to you that they were building a two story, single-family home on the site, your foundation and bearing assessment would be based on that information. If the client then decided to build a six story, multi-family complex, your provided calculations may no longer be valid and the resulting structural design could be inadequate. If you did not clearly identify the scope of the report, as you understood it, you could be drug into the resulting litigation. For identifying the project, you want to establish a chain of events. An example is shown below.

Example

> Bad Wolf Engineering, INC. retained Very Good Geotechnical Testing, INC. to perform a geotechnical engineering study for the dvelopment of a multi-story, multi-family housing complex located at 1776 Murica Dr., Tuscaloosa, AL. The site is shown in Figure 1 in Appendix A of this report.

This clearly indicates that everything in the resulting geotechncial report is for a multi-story, multi-family housing complex. It also indicates that Bad Wolf Engineering, INC. retained you to complete the work. For a big project, there could be several engineering firms so it is important to outline who is actually requesting the geotechnical report.

Continuing the theme of clarity, a multi-story, multi-family housing complex is not sufficiently clear. Our next step should be to describe the project in as much detail, as we understand it, and highlight the deficiencies in our understanding. See the example below.

Example

> The proposed multi-story, multi-family housing complex is located south of Elm St., east of Mulholland Dr., west of Fleet St., and north of Woodland Rd. in Tuscaloosa, Tuscaloosa County, Alabama. We understand the proposed development consists of the design and construction of a multi-story, multi-family housing complex at 1776 Murica Dr., Tuscaloosa, AL. The preliminary structural design and grading plans were not available for review and evaluation. The anticipated structural loads for the proposed project are assumed to be 6 kips/ft for continuous footings and 100 kips for column footings. The building footprint area is 3,000 sq. ft. Any geotechnical design or recommendations in this report are based on these assumptions. If any of the assumed information is inaccurate or the project scope changes, please inform Very Good Geotechncial Testing, INC. so that we may review our recommendations and make revisions as needed.

When you are retained by a client to perform work at a site, you will generally provide a list of services you are to perform. Sometimes the client will provide you with a scope of services and other times will expect you to provide a recommended scope of services. It is important to explicitly list all services listed in the scope of work for the project. This acts as a checklist for both you and the client to ensure the contract was executed satisfactorily. A partial example is shown below.

Example

In order to obtain the required subsurface information, the Scope of Work has been presented below for this site.

1. Very Good Geotechnical Testing, INC. contacted the 811 locate service to obtain underground public utility clearance prior to commencing field work.

2. Reviewed readily published geologic information from USDA NRCS.

3. Executed five Hand Auger Borings (HAB) to a depth of 4 feet and performed testing in accordance with ASTM D1452.

4. Visually classified and stratified representative soil samples per ASTM D3282 and D2487.

5. Prepared this formal engineering report summarizing the field exploration, lab testing, engineering analyses, and recommendations.

10.5 Site Description Overview

This section of a geotechnical report is a high level view of the site. You will typically compile published data from the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS), the United States Geologic Survey (USGS), and/or local agencies regarding the physiographic and geologic setting and the general soil conditions. This information will typically include the physiographic section/district, geologic unit(s), soil and rock descriptions, soil classifications, and seasonally adjusted groundwater table, among other items[23]. In all presentations of the data, it is important to format it yourself and not screenshot the source for the sole reason of looking professional. For example, in presenting your soil data, create your own table and do not take a screenshot from the Web Soil Survey website. See below for an example.

[23] It's a good thing you already did this in your earlier homework assignment!

Example

The Soil Survey of Hillsborough County in Tampa Area, Florida published by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) was reviewed for general near-surface soil information. Refer to Figure 2 in Appendix A for a reproduction of the NRCS map for the project area, and the soil survey summary in Table 10 below.

Table 10. Soil Survey Summary

Soil Unit	Depth, in	Description	USCS	SHGWT*, ft
	0–5	Fine Sand	SP	
Winder	5–14	Fine Sand	SP	0–1
(60)	14–18	Sandy Clay Loam	SP	
	18–34	Sandy Clay Loam	SP	

*Seasonal High Groundwater Table

Some clients will also require some approximate topographical information, especially when the site is undisturbed (i.e. no previous development exists). The United States Geological Survey publishes topographical maps that can be used for this purpose. It is extremely important to acknowledge that a licensed professional engineer is not a licensed professional surveyor and cannot legally comment on metes and bounds, boundaries, and exact elevation features. An example of an appropriate level of detail that a licensed professional engineer can describe is shown below.

Example

The "Hillsborough County in Tampa Quadrangle" USGS Topographic Survey Quadrangle Map issued in 2018 was reviewed for ground surface features. Based on Very Good Geotechnical Testing, INC. review, the natural ground surface at the project location appears to be nearly level at approximately +15 feet relative to North American Vertical Datum of 1988 (NAVD-88). The site is located within Section 26, Township T26 and Range R19 in Hillsborough County, Florida.

10.6 Testing Methodology

Nearly all geotechnical investigations have both a field and laboratory investigation plan. For this exercise, the only field work you conducted was the sand cone test, so that portion of your report will be small. In practice, the field investigation portion contains the testing procedures used for borings, hand augers, double-ring infiltration testing, etc. and can be quite extensive. However, there is extensive laboratory testing that you conducted that will need to be included in the report. For both field and laboratory reports, it is important to be succinct, accurate, and, most importantly, note any deviations from accepted practices.

An example of a sufficient field testing methodology description and laboratory testing methodology is shown below.

Example

Hand auger borings were performed to a depth of six (6) feet below natural grade by manually twisting and advancing a bucket into the ground to 6-inch increments. This boring was performed in general accordance with the American Society of Testing and Material (ASTM) Testing designation D-1452. As each sample was revealed, representative samples were placed in air-tight jars and returned to our laboratory for visual examination and classifications by the licensed geotechnical engineer.
The laboratory tests were conducted in general accordance with ASTM specifications. The laboratory test results are summarized in Table 11 below. The ASTM method number for each test and the number of tests completed are presented in the following table, and the results of the tests are in Table 1 in Appendix D.

Table 11. Laboratory Testing Executed

Description	Number of Tests	ASTM Test Method
Gradation	5	D6913
Moisture Content	2	D2216
Classification	10	D2487/D2488

10.7 Subsurface Soil Conditions

This is the heart of your geotechnical report. This section will summarize the findings from your investigation. In most reports, the results from the soil borings are the key portion of this section. The laboratory testing results are typically not mentioned and the data is simply provided in an appendix. However, your report will focus more on the laboratory findings as you will not have a boring report. This section of the report is meant to summarize your findings, not present each and every test result you obtained. Since we are deviating from what is in a typical report, there is no good example to provide. However, at a minimum, this section of your report should contain the following:

- USCS classification
- AASHTO classification
- Optimum moisture content and maximum dry density
- Field measured density and compaction percentage

Your presentation should be mostly in narrative form. Your appendix will contain the raw data and graphs. An example of how to take graphical data (i.e. sieve analyses) and "convert" them into a narrative is shown below.

Example

A sieve analysis was performed on the two soil samples. Sample A was a clayey soil with a USCS classification of CH and an AASHTO classification of A-6(20). This soil had an OMC of 12% and was found to be compacted to 93% MDD in the field.

The second sample, Sample B was a gravel material with a USCS classification of GW and an AASHTO classification of A-1-a(0). This soil was not part of the compaction process and thus no moisture density curve or compaction values are available.

10.8 Design Calculations and Recommendations

From a professional licensure point of view, this is the most important part of the report. You are legally liable for the calculations and recommendations you provide in this section. Engineers have gone to jail for miscalculations when they lead to loss of life. While it is not likely you will be imprisoned for a miscalculation on a residential geotechnical report, you could very easily be sued if that miscalculation cost the client money in loss of time or additional materials to address the inadequacy.

Additionally, this section of a geotechnical report is very specific to the proposed project. For a residential project, assuming the soil conditions are sufficient, a general design will be proposed and this design is identical for a specific range of soil conditions. An example of such language is shown below. In this example, there is no specific mention of design loads because they were not known at the time of the report. Recall earlier in the example report it was assumed that continuous footings could support 6 kips/ft.

Example

The area that will support the single-family home should be properly prepared; all topsoil and unsuitable materials should be removed to a 3-foot distance beyond the perimeter of the structure. Unsuitable materials include the following: topsoil, concrete, asphaltic concrete, buried structures, rubbles, any soft soil and miscellaneous fill. Any buried utility lines within the construction limits should be located, removed, and relocated outside the construction area.

Suitable structural fill/backfill material for the excavated area should consist of an inorganic, non-plastic, granular soil containing less than 10 percent material passing the No. 200 mesh sieve (relatively graded gravel or a crushed lime-rock with a two-inch maximum particle size) with a Unified Soil Classification of GP, GW or SP or similar to #57 stones. It shall be clean, shall not be expansive nor have high organic content, and shall be free of clay, marl, unstable materials and debris.

The structural backfill of the foundation pad should be compacted to a density of at least 95 percent of the ASTM D-1557 maximum dry density. The required compaction should be achieved for a depth of at least one and a half (1.5) feet below the bottom of the bearing surface. Lean concrete can also be used as a backfill material to achieve sufficient bearing capacity in poor soil conditions.

Required Calculations

For your report, the client wants to use foundation pads that will be 24 inches by 24 inches and 12 inches thick. The allowable load on each pad is 10,000 lb_f. Unfortunately, Very Good Geotechnical Testing, INC. forgot to include triaxial testing in their scope of work and there is no friction angle data available. You should assume a reasonable friction angle for a clayey soil and use the previously calculated unit weights to determine the factor of safety of the clients design.

If a sufficient factor of safety exists, you can state that the design as-is appears to be adequate but any changes to the design loads should be re-evaluated. If the factor of safety is below the generally accepted values, state that the client should retain your services to design a better foundation and that construction should not begin until a proper foundation has been designed.

10.9 Report Limitations

What would any engineering report be without a bunch of disclaimers. We are not environmental engineers. We are not structural engineers. We are not professional surveyors. We are geotechnical engineers and thus our findings and data analysis are limited to our field. See below for a good example of how to limit your liability.

Example

Our professional services have been performed, our findings obtained, and our recommendations prepared in accordance with generally accepted geotechnical engineering principles and practices. The recommendations provided in this report are based on design concepts, parameters and constraints made known to this firm. The final design may require revision of the recommendations provided herein and should consider the findings of the complementary subsoil exploration scheduled to be performed once the existing building is demolished. We are not responsible for the conclusions, opinions or recommendations made by others based on these data.

The scope of the exploration was intended to evaluate soil conditions within the influence of the foundations systems considered in this report. It does not include any evaluations of deep potential soil problems such as sinkholes. The analysis and recommendations submitted in this report are based upon the data obtained from the soil borings performed at the locations indicated and does not reflect any variations which may occur among these borings. If any variations become evident during the course of this project, a re-evaluation of the recommendations contained in this report will be necessary after we have had the opportunity to observe the characteristics of the conditions encountered. The applicability of the report should be reviewed in the event significant changes occur in the design, nature or location of the proposed structures.

The scope of services included herein, did not include any environmental assessment for the presence or absence of hazardous or toxic materials in the soil, surface water and groundwater, air on the site, below and around the site. Any statements in this report or on the boring logs regarding odors, colors, unusual or suspicious items and conditions are strictly for the information of the client.

10.10 Final Geotechnical Report

This is it, your final deliverable! Using the information in this lab manual and the real-life example report on Blackboard, create your own geotechnical report. At a minimum, you should have:

- ☐ Cover Letter
- ☐ Project Description and Scope
- ☐ Site Description Overview (i.e. Web Soil Survey, map of location and references to streets and other landmarks)[24]
- ☐ Testing Methodology
- ☐ Subsurface Soil Conditions
- ☐ Design calculation for foundation load and general recommendations
- ☐ Limitations
- ☐ Appendices of all your lab deliverables. Each deliverable should be in its own appendix (i.e. Appendix A, B, etc).

A lot of the content will be copied and pasted. You can look at the real-life example report and realize that a lot of it could easily be re-used for each geotechnical report. It is perfectly acceptable to do that provided the statements remain accurate for the specific project[25].

[24] You need to use the location from your homework assignment.

[25] The biggest reason students lose points is that they directly copy and paste without modifying the statements to ensure they are appropriate for the specific site. You will lose substantial points for failing to adapt the provided statements to your specific project. For example, students in the past have copied the section from this manual indicating they performed hand auger borings. Really?! We're not doing that in lab so you can't say you did it in your report!

Appendix A: Required Worksheets For Lab Use

CE340 Sieve Analysis Worksheet

	Starting Mass:	**Starting Mass:**	**Starting Mass:**

Sieve	**Clayey Soil (ASTM D6913)** Mass of Empty Sieve (g)	Mass of Soil + Sieve (g)	**Sandy Soil (ASTM C136)** Mass of Empty Sieve (g)	Mass of Soil + Sieve (g)	**Coarse Aggregate (ASTM C136)** Mass of Empty Sieve (g)	Mass of Soil + Sieve (g)
1 1/2"						
3/4"						
1/2"						
3/8"						
#4						
#8						
#10						
#16						
#20						
#30						
#40						
#50						
#60						
#100						
#200						
Pan						

Notes:

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CE340 Hydrometer Analysis Worksheet

Mass of Starting Moist Soil Sample		g
Meniscus Correction Factor (C_m)		g soil/L
Average Mass Shift of 152H Hydrometer (B)	**4.3**	g soil/L
Specific Gravity of Soil Particles (G_s)	**2.65**	
Maximum Distance from Buoyancy (H_{r1})	**18.3**	cm
Minimum Distance from Buoyancy (H_{r2})	**3.4**	cm
Maximum Hydrometer Reading (r_1)	**50**	g soil/L
Minimum Hydrometer Reading (r_2)	**0**	g soil/L
Cross Sectional Area of Graduated Cylinder (A_c)	**26.5**	cm^2
Volume of Hydrometer Bulb (V_{hb})	**66**	cm^3
Volume of Suspension (V_{sp})	**1000**	cm^3

Notes:

Time of Reading, min	Hydrometer Reading (r_m), g soil/L	Temperature at time of reading, °C
1		
2		
5		
8		
15		

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CE340 Atterberg Limits Worksheet

Measurement	Units	Plastic Limit 1	Plastic Limit 2	Plastic Limit 3	Liquid Limit 1	Liquid Limit 2	Liquid Limit 3
Blows	#						
Pan ID	--						
Dry Soil*	g						
Added water	g						
Moisture Content**	%						
Target MC	%						

Notes:
* Remember to tare scale after putting container on it.
** Moisture content is mass of water divided by mass of solids.

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CE340 Standard Proctor Worksheet

Measurement	Units	Sample 1	Sample 2	Sample 3
Pan ID	--			
Mold Diameter	in			
Mold Height*	in			
Mass Empty Mold	g			
Mass Soil + Mold	g			

Notes:
* Height of the base portion; do not include the upper ring.

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CE340 Sand Cone Worksheet

Sand Unit Weight	Height	______
	Diameter	______
	Empty Mass	______
	Filled Mass	______
Cone Calibration	Starting Sand Cone Mass	______
	Ending Sand Cone Mass	______
Field Measurement	Starting Sand Cone Mass	______
	Removed Soil Mass	______
	Ending Sand Cone Mass	______
Moisture	Container ID	______
	Empty Container Mass	______
	Moist Soil + Container	

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CE340 Permeability (Constant Head) Worksheet

Measurement	**Units**	Trials **1**	**2**	**3**
Discharge Volume	mL	100	100	100
Sample Height	cm			
Time to Discharge	s			
Height Between Outflow and Overflow	cm			

Notes:

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Appendix B: Example Complete Gradation Report

SIEVE ANALYSIS

AASHTO T-27 / T-11

Client:

Report Date:
Project:

Contact:
Phone:

Project No:

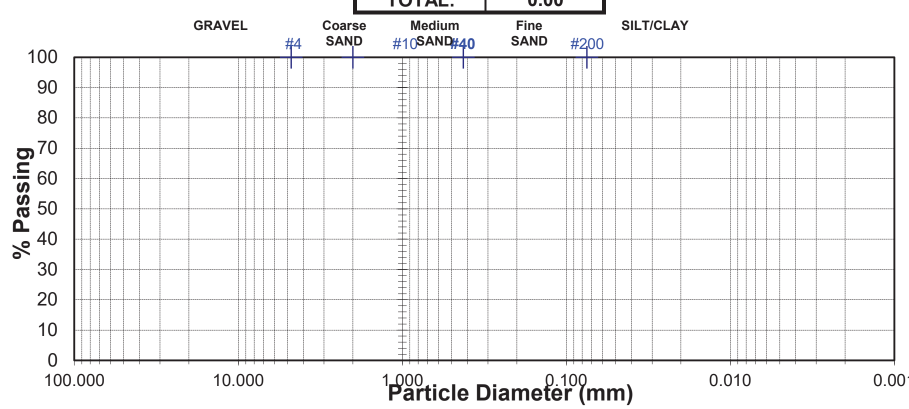
Sample Information

Location:		**Tested By:**		**Test Date:**	
Boring No:		**Checked By:**		**Gnd Elev.:**	
Sample Depth:		**Sample ID:**			

Lab Results

USCS Soil Classification:
AASHTO Soil Classification:
Weight of Dry Sample (g):

Sieve Number	Diameter (mm)	Mass of Sieve (g)	Mass of Sieve & Soil (g)	Soil Retained (g)	Soil Retained (%)	Cumulative Retained (%)	Soil Passing (%)
2"	50.800						
1 1/2"	38.100						
1"	25.400						
1/4"	19.050						
#4	4.760						
#10	2.000						
#20	0.841						
#30	0.595						
#40	0.400						
#50	0.297						
#60	0.250						
#100	0.150						
#200	0.074						
Pan							
#200 Wash							
			TOTAL:	**0.00**			



Grain Size Distribution Curve Results:			
% Gravel:		**D_{10}:**	
% Sand:		**D_{30}:**	
% Fines:		**D_{60}:**	
		C_u:	
		C_c:	

Moisture Content & #200 Wash			
Can:			
Wet + Care:		**Start Wt (g):**	
Dry + Can:		**After Wash:**	
Wet - Dry:		**Before - After:**	
Moisture		**-200 %:**	

Appendix C: Example Hydrometer Report

HYDROMETER ANALYSIS OF SOIL BINDER

Sample No. ________

Hydrometer No. ________ Date ________ Starting Time ________

% Soil Binder ________ % Hgy Mc ________ Weight of Air Dry Sample (g) ________

Ret. on No.40 ________ Sp. Gr. ________ Corr. Weight of Sample (g) ________

Composite Corr. ________ Temp. C° ________ Correction Factor, a ________

Hydrometer Reading	Corr. Hyd Reading	% Soil in Suspen.	Time Min.	Eff. Depth L,cm	Constant K	Grain Dia mm

Appendix D: Example Atterberg Report

REVERSE

STATE OF NEW YORK
DEPARTMENT OF TRANSPORTATION
SOIL MECHANICS BUREAU
ATTERBERG LIMIT TESTS

Date ______________

Test by ______________

Comp. by ______________

Check by ______________

Project ____

Region ____________ County ________________________ Contract ______________________

Sample No. ________ Depth - m ________		LIQUID LIMIT - %			PLASTIC LIMIT - %	
1.	Tare No.					
2.	Tare Plus Wet Soil					
3.	Tare Plus Dry Soil					
4.	Wt. of Tare					
5.	Moisture Loss (2 - 3)					
6.	Wt. Dry Soil (3 - 4)					
7.	% M.C. (5) ÷ (6) × 100					
8.	No. of Blows					

$\frac{0.075}{0.425}$ = ______ %

Liquid Limit ________

Plastic Limit ________

Plastic Index ________

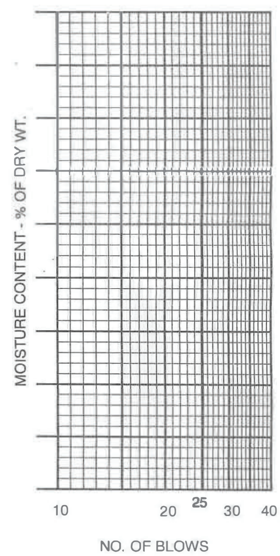
Sample No. ________ Depth - m ________		LIQUID LIMIT - %			PLASTIC LIMIT - %	
1.	Tare No.					
2.	Tare Plus Wet Soil					
3.	Tare Plus Dry Soil					
4.	Wt. of Tare					
5.	Moisture Loss (2 - 3)					
6.	Wt. Dry Soil (3 - 4)					
7.	% M.C. (5) ÷ (6) × 100					
8.	No. of Blows					

$\frac{0.075}{0.425}$ = ______ %

Liquid Limit ________

Plastic Limit ________

Plastic Index ________



Appendix E: Example Compaction Report

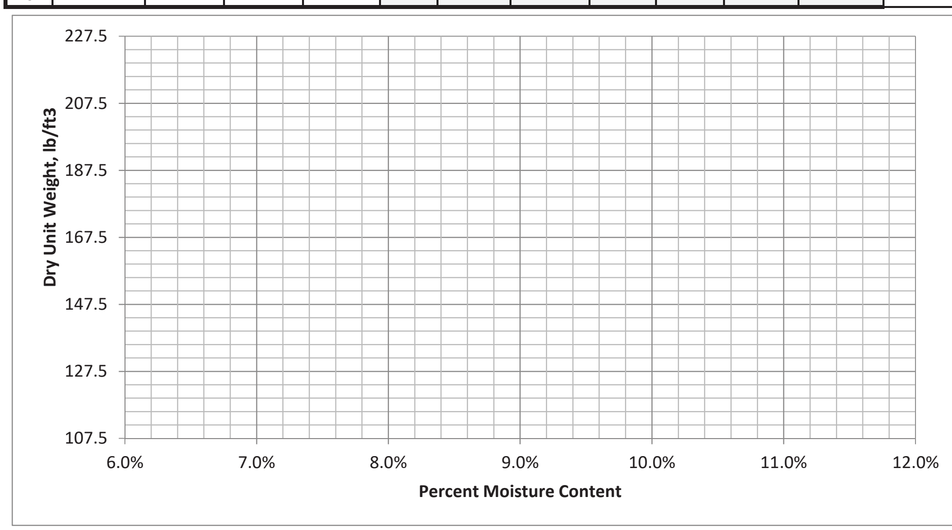
Compaction (Proctor)

Client:
Project:
Project NO:

Report Date:
Tested By:
Test Method:

Material Information		
Lab ID: ______	Date Sampled: ______	Maximum Compaction: ______
Material Use ______	Date Received: ______	Optimum Moisture Content: ______
Material Description:		

Laboratory Results												
					Moisture Content Determination							
Trial	Mass of Compacted Soil+Mold Msm (g)	Mass of Mold Mm (g)	Mass of Compacted Soil (g)	Wet unit Weight γwet (lb/ft3)	Can ID	Mass of Wet Soil + Can, Mcws (g)	Mass of Dry Soil +Can, Mcs (g)	Mass of Water Mw (g)	Mass of Can Mc (g)	Mass of Dry Soil Ms (g)	Moisture Content w(%)	Dry Unit Weight γd (lb/ft3)
A	B	C	D	E	F	G	H	I	J	K	L	M
1												
2												
3												
4												
5												



Mold Dimensions (in):
Dia: ______ Area: ______
Ht: ______ Volume: ______

Compaction Energy
Hammer Wt: ______
Drop (in): ______
Blows per lift: ______

Comments:

Appendix F: Example Sand Cone Report

DENSITY TEST WORKSHEET - SAND CONE METHOD

North Dakota Department of Transportation, Materials & Research

SFN 59725 (5-2019)

Project Number	PCN	Date	Tested By	Tech ID

TEST IDENTIFICATION		**Test Number**					
		Time					
		Lot					
		Station					
		Offset from centerline					
		Lane					
		Depth below finished grade ft.					
IN-PLACE DRY DENSITY DETERMINATION	a	Unit Weight of Sand (pcf) SFN 59724					
	b	Wt. material removed from test hole-lbs.					
	c	Initial sand weight - lbs.					
	d	Final sand weight - lbs.					
	e	Wt. sand in funnel and hole = c - d					
	f	Cone calibration factor- lbs. SFN 59724					
	g	Wt. sand in hole = e - f (lbs.)					
	h	Volume of test hole = g/a (cu. ft.)					
	I	Wet Density = b/h/(lbs./cu. ft.)					
	j	Dry Density = i/(100+p) x 100(lbs./cu.ft.)					
		Moisture Determination					
	k	Wet weight + container					
	l	Dry weight + container					
	m	Moisture loss = k - l					
	n	Tare weight of container					
	o	Dry weight of soil = l - n					
	p	Moisture Percentage = (m/o) x 100 (%)					
MOISTURE-DENSITY RELATIONSHIP TEST		ND Procedure					
		Test Number (Proctor Test)					
		Station					
		Offset from centerline					
		Depth below finished grade					
	q	Maximum Dry Density					
		Optimum Moisture					
REQUIRED MOIS-DENS.		Required % maximum Dry Density					
		% Maximum Dry Density = (j/q) x 100					
		Required Moisture					
		Moisture = p					

Remarks

Appendix G: Example Permeability Report

CONSTANT HEAD PERMEAMETER TEST RESULTS

Material Information		
Lab ID: ________	Date Sampled: ________	Date Received: ________
Material Use: ________		
Material Description:		

Trial	Sample Height, cm	Cross Sectional Area, cm2	Head, cm	Unit Volume, mL	Time to Fill Unit Vol., s	Coeff. Permeability, cm/s
1						
2						
3						
4						
					Average Permeability Coefficient	

Notes: